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INSTRUMENTATION SYSTEM FOR HIGH SPEED DATA SAMPLING OF ELECTRIC--ETC(U)
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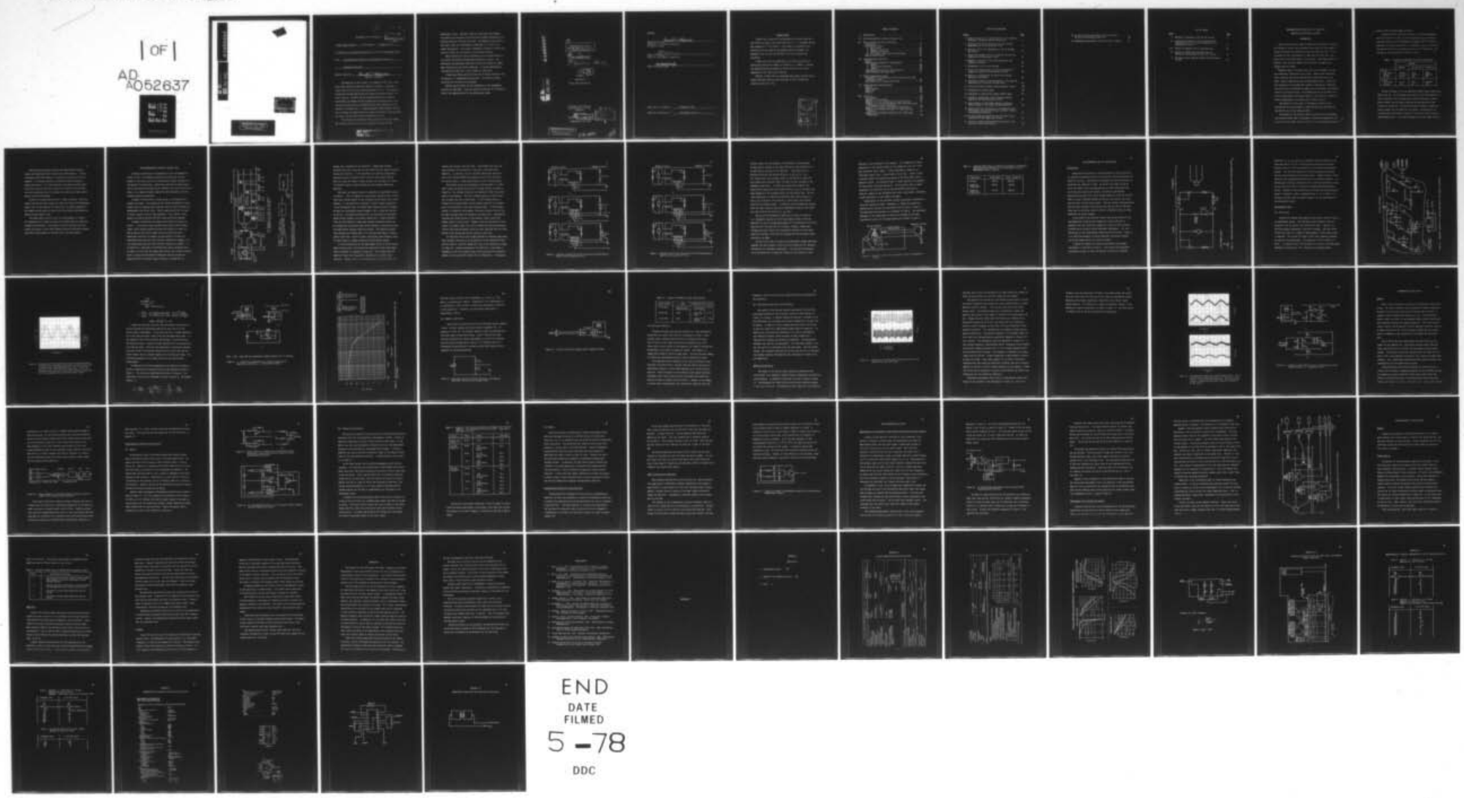

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AN ABSTRACT OF THE THESIS OF

Glen Edward Brisbine for the degree of Master of Arts

in Electrical and Computer Engineering presented on 23 December 1975.

Title: Instrumentation System for High Speed Data Sampling of Electrical Machinery

Abstract approved: Gerald C. Alexander

Gerald C. Alexander

The objective of this thesis is to develop criteria for a data acquisition system for electrical machinery capable of sampling a signal every 0.2 msec with a desired accuracy of 0.1%. The system to be measured includes both AC and DC voltage and current signals from several points. The main item of installed equipment from which measurements were taken for test purposes was a motor-generator (MG) set and an exciter which are located in the power laboratory in the basement of Dearborn Hall. A Texas Instruments 960A computer complete with an analog to digital conversion system (multiplexer, A/D converter, and sample and hold amplifier) was available for use.

The criteria are developed from an analysis of the environment, the installed equipment and several possible circuits for the

measurement system. Machinery coupling capacitances and leakage resistances are discussed as are the noise voltages, unbalances, and voltage transients resulting from them. The magnetic noise pickup in the signal loops was investigated to determine its effect on the signal transmission. The exciter frequencies (inherent) are analyzed and their effect on the accuracy of the system discussed.

Noise minimization circuit principles are discussed briefly as are several fabricated instrumentation amplifier circuits. The fabricated instrumentation amplifier circuits are tested for common mode rejection and the results tabulated. A typical manufactured instrumentation amplifier is also tested for comparison.

A data acquisition system for both the DC and AC circuits of the AC generator is recommended and discussed. The results of tests utilizing the DC circuit are discussed.

General specifications for the components of the recommended circuits are developed. These are general guidelines for the acquisition of the component parts of the measurement system.

(6)

Instrumentation System for High Speed Data Sampling of Electrical Machinery.

by

(10) Glen Edward Brisbine

(9) Master's thesis,

(12) 72p.

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Arts

(11) Completed 15 December 1975

Commencement June 1976

272 200

VB

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Date thesis is presented 23 December 1975

Typed by Linda Morgan for Glen Edward Brisbine.

ACKNOWLEDGMENT

I would like to gratefully acknowledge the patience shown and the willing assistance and advice given by Dr. G. C. Alexander during the preparation of this thesis. Even though not employed by the University and only home on the weekends during the summer, Dr. Alexander still gave of his available time for discussion and assistance.

I would also like to acknowledge the willing assistance and advice given during the summer by Professor L. C. Jensen. Although not employed during the summer by the University, he also gave generously of his time in assisting me.

Finally, I would like to acknowledge the support given me by my family and thank them for their endurance of this strained and tested period of our life.

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INTRODUCTION

One of the basic tools used in industrial development is modeling. If a system or process can be modeled, then changes to the system or factors affecting the system can be observed from the model. The use of models for this investigation is much less expensive than tests which utilize the actual process or equipment. Even though models do provide a cost savings, industry still demands a "minimal cost, maximum accuracy" model.

Computer models of AC generators have been developed, but they are cumbersome, complicated, and lengthy. Reducing the complexity while retaining sufficient accuracy would reduce the cost of the model, thereby reducing the test and development costs. High speed data sampling of an AC generation system is required to investigate the possibility of modifying the model, and, to determine the accuracy limits of the revised model. Verification of the revised model will require measurements from several points in the electrical system as nearly simultaneously as possible and at short intervals.

The objective of this paper is to develop criteria for an instrumentation system capable of acquiring the data necessary for the modification of the computer model.

Development of the criteria involves analyzing the environment, the available major items of equipment (installed and moveable), the variables of the model, and the acquisition and processing of quality

analog signals of these model variables.

The main items of installed equipment from which measurements were to be taken are an MG set and an exciter which are located in the power laboratory, in the basement of Dearborn Hall. The MG set consists of a synchronous motor, a DC generator, and an AC generator. The exciter consists of an induction motor and a DC generator. The ratings of this equipment are listed in Table I.

TABLE I. RATINGS OF COMPONENTS OF MG SET AND EXCITER

	Ratings		
	Output	Current (A)	Voltage (V)
MG set			
syn. motor	125 HP	31.5	2200
AC gen.	37.5 KVA	99/171	220/127
DC gen.	50 KW	200	250
Exciter			
ind. motor	7.5 HP	20/10	220/440
DC gen.	5 KW	40	125

Several variables in the AC generation system require measurement. Among these are: the DC voltage and current at the field terminals of the AC generator, the AC voltage and current of each phase (three phase system), and the angular velocity and acceleration of the exciter and the MG set. As part of the model testing, variable frequency signals will be applied to the system. Previous work has indicated that the maximum frequency of interest in the DC system is approximately 20 Hz. The normal frequency of the AC system is 60 Hz.

High speed data sampling requires the acquisition of analog signals and automated digital conversion of those signals. A Texas Instruments model 960A computer is available to process the signals obtained. The computer contains an analog-to-digital conversion system (multiplexer, 12 bit A/D converter, and sample and hold amplifier) which requires the input signal to be scaled to plus or minus ten volts maximum and which is capable of processing a signal approximately every 25 microseconds.

An error of no more than one part in 1000 is desired. Since the sample and hold amplifier tracks the signal and relays an instantaneous signal level to the computer for conversion, the signal presented to the sample and hold amplifier must be as noise free as practicable to insure accurate digital data.

This paper deals primarily with the establishment of criteria for presentation of a quality signal to the sample and hold amplifier through the multiplexer. The purpose is not to construct the final system, but rather to test those elements which are available to determine their effectiveness for possible use in the final system.

THE INSTRUMENTATION SYSTEM--A GENERAL LOOK

A primary consideration in development of the instrumentation system is that it be capable of acquiring voltages and currents present at the pickup point and of delivering a signal acceptable to the computer for processing. Connections required for proper operation of the generation system and the computer must also be considered. Figure 1 is a general diagram showing the major equipment available, including required connections.

A number of transformers, current shunts, and voltage divider networks are shown. The presence of the current and potential transformers tends to suppress noise coupling into the signal channels for measurements from the AC lines. The DC signal acquisition as shown is direct, however, with no such isolation. Thus, the DC circuit appears to contain the more difficult data acquisition problems.

A number of amplifiers and other active devices are shown in Figure 1. The current shunts available were rated at 50 mV output signal, which requires amplification of the signal by a factor of 200 to obtain a full scale signal of plus or minus ten volts. Operational amplifiers in general can be operated in either the differential mode (neither input terminal connected to common) or in the single-ended mode (one input terminal connected to common). If an amplifier is operated in the differential mode, precautions must be taken to insure that the common mode voltage (the voltage reference that is common to both amplifier terminals) does not exceed the absolute value of the power supply voltage at the amplifier or

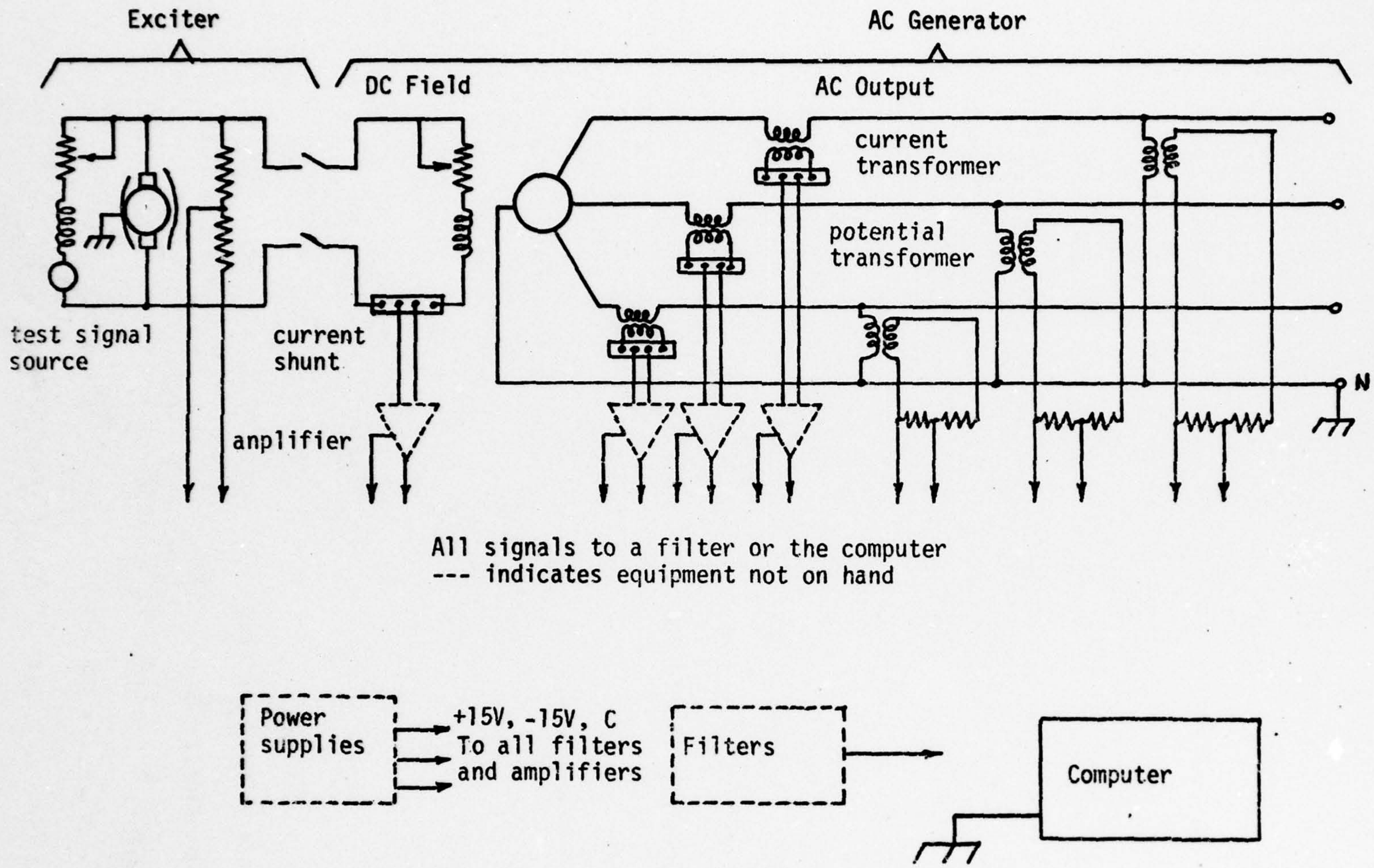


Figure 1. General diagram of the system showing major equipment available, including required instrumentation connections.

perhaps less, depending on the amplifier. Common mode voltages exceeding the limits specified for each amplifier will almost certainly destroy the amplifier. If the amplifiers are operated single-ended, precautions must be taken to insure that the input signal voltage does not exceed the supply voltage, because such voltages will result in incorrect output voltage readings and will probably damage the amplifier.

Note that the computer ground is connected to experimental ground in Figure 1. This is required to insure proper operation and to insure that stray voltage signals do not accidently cause faulty logic in the computer. If the amplifiers connected to the DC signal are operated in the differential mode, the common mode voltage on them will depend on where the experimental ground (common) line is connected into the DC circuit. The multiple possibilities for connection of the experimental ground (common) line require examination. Primary considerations are that amplifier common mode voltage limitations should not be exceeded and that ground loops which introduce circulating currents and undesireable voltages should be avoided. The problem of ground loops becomes more complex when it is observed that Figure 1 contains several amplifiers, several filters, and several power supplies, each of which requires a common connection to experimental ground.

A first consideration of the measurement points of the DC circuit might indicate that a single amplifier operating in the single-ended mode is adequate as suggested in Figure 2a. This assumes that the amplifier inputs can be physically located at the current shunt terminals. However, this is not possible and the amplifier will be

located some distance from the shunt. Lead lengths and dress may cause unbalance to the amplifier, which has a very high input impedance. In addition, not all available operational amplifiers have a well defined common with respect to their input terminals. For these reasons, a single-ended amplifier may be unsatisfactory.

The voltage across the AC generator field terminals is a high level signal and should only require a voltage divider as shown in Figure 2a. The voltage divider can be located at either the current shunt or the computer. The noise voltage picked up in the circuit will be about the same in both cases. If the voltage divider is located at the current shunt, the DC voltage signal will be reduced prior to the addition of the noise voltage signal. If the voltage divider is located at the computer, the noise voltage as well as the DC signal voltage should be reduced by the same ratio. Consequently, locating the voltage divider at the computer should provide the highest signal to noise ratio. However, with this particular circuit layout, the common signal line of the voltage and current measurement circuit could provide another source of error resulting from the interaction of the voltage and current signals on that line.

If lead dress and circuit layout problems do introduce appreciable noise voltage, then the use of an amplifier in the differential mode with an explicit amplifier common will need to be considered as shown in Figure 2b. Accurate operation of the amplifier in this mode is dependent on the stray voltage signals being balanced with respect to common at the two amplifier inputs for all frequencies. If unwanted

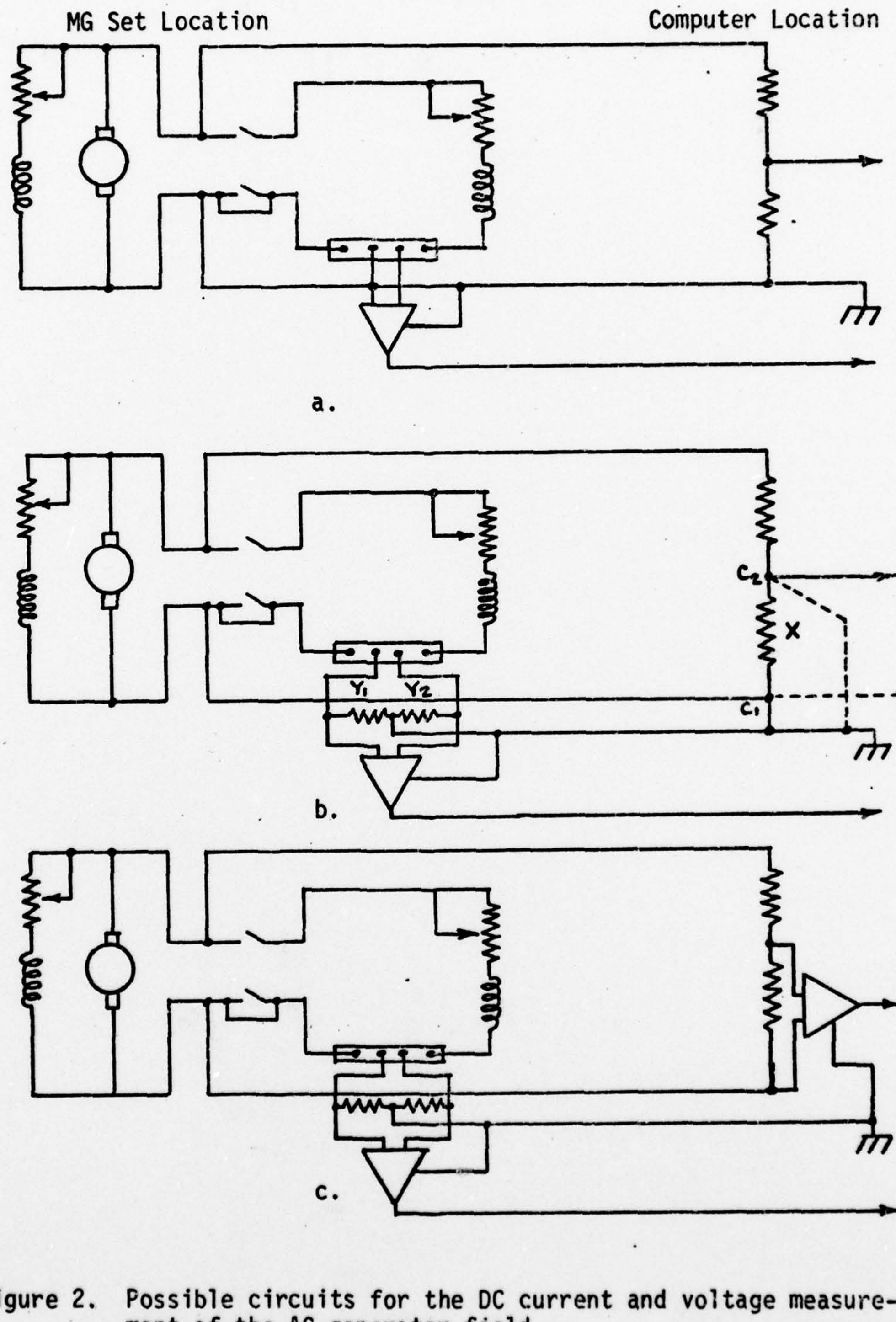


Figure 2. Possible circuits for the DC current and voltage measurement of the AC generator field.

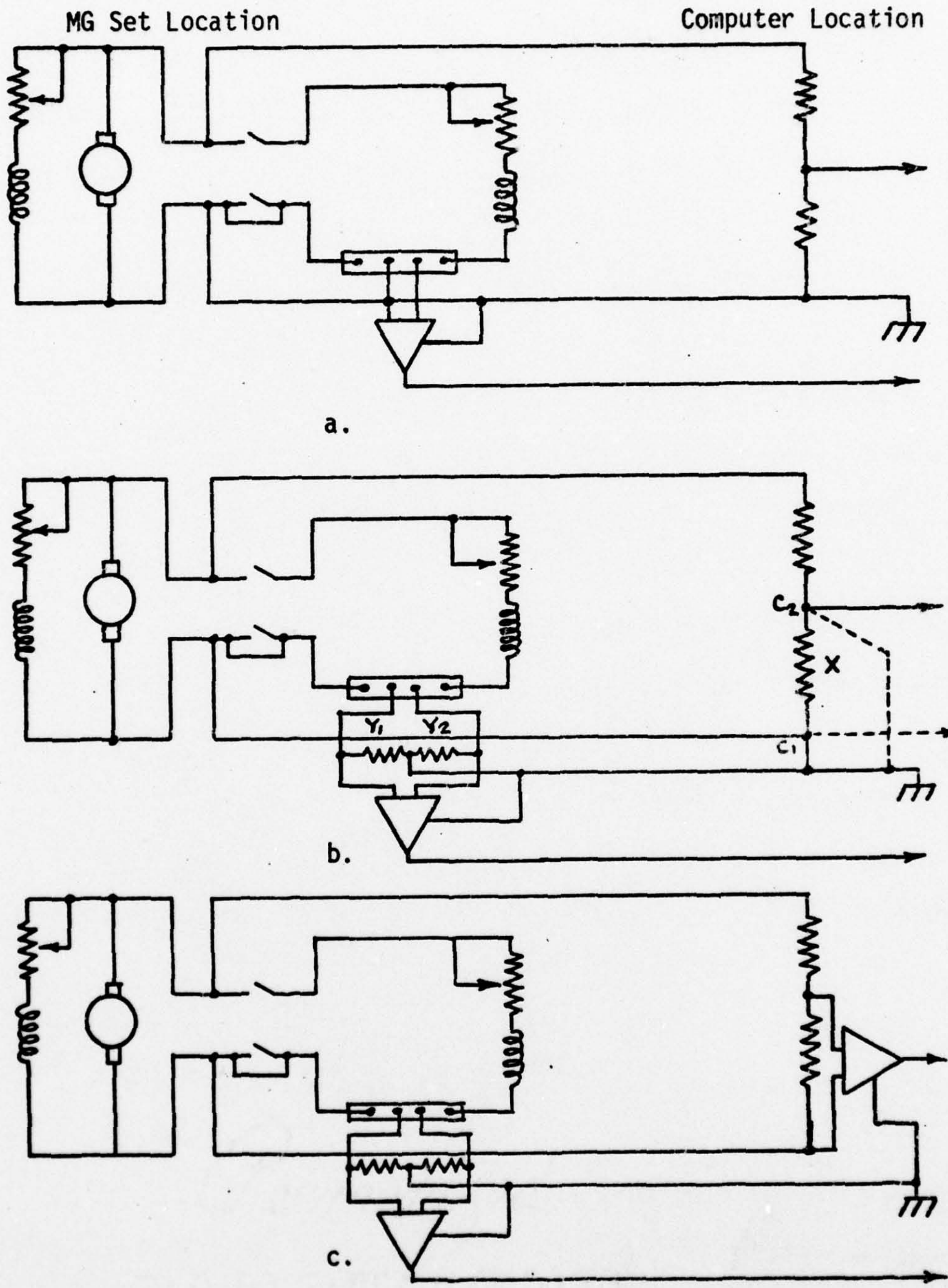


Figure 2. Possible circuits for the DC current and voltage measurement of the AC generator field.

voltage signals are not balanced, the difference of the unwanted voltage signals present at the input terminals of the amplifier will be amplified by the gain of the amplifier. Inserting a pair of balanced relatively low valued resistors, Y_1 and Y_2 ($Y_1 = Y_2$), will balance the stray voltage signals at the amplifier inputs for good common mode rejection (CMR), but they can also introduce a low impedance ground loop. To reduce the ground loop currents, the experimental ground point can be moved from C_1 to C_2 to introduce the high impedance of the voltage divider into the ground loop. But now, close examination of Figure 2b as modified shows that resistors Y_1 and Y_2 are in parallel with resistor X, which upsets the dividing ratio of the voltage divider. In addition, the DC common mode voltage level has been raised by moving the experimental ground to the center tap, which limits the sizes of Y_1, Y_2, and X.

The use of two differential amplifiers as shown in Figure 2c is a reasonable solution to the DC measurement problem. Since the amplifier for the DC voltage measurement will be operated at unity gain, lead dress will be much less of a problem. However, common mode voltages and noise levels must be carefully examined to insure that amplifier tolerance limits are not exceeded and that processed signal accuracies are known.

The AC circuit does not contain the experimental ground connection problems that were present in the DC circuit because of the isolation provided by the instrument transformers. The potential transformers can be connected with a common bus running to the computer or with

individual lines connected at the computer. If a common bus is used, interaction of the voltage signals on the common bus line will introduce additional noise signals. Either alternative, common bus or individual common lines, is practicable in this case. Figure 3 shows a possible method of connecting one phase of the three phase instrumentation system. The voltage divider is shown located at the computer for the reasons indicated previously. The AC current shunt is shown connected to an amplifier used in the differential mode with an explicit common, on the assumption that truly single-ended, integrated-circuit amplifiers are not readily available.

Investigation of the available current and potential transformers, using the connections shown in Appendix VI, showed the capacitive coupling values between the transformer coils as given in Table II. The capacitance was measured at a frequency of 1000 Hz. The equivalent impedance of the capacitances at 60 Hz are included in the table. Equivalent circuits for the capacitances are included in Figure 3.

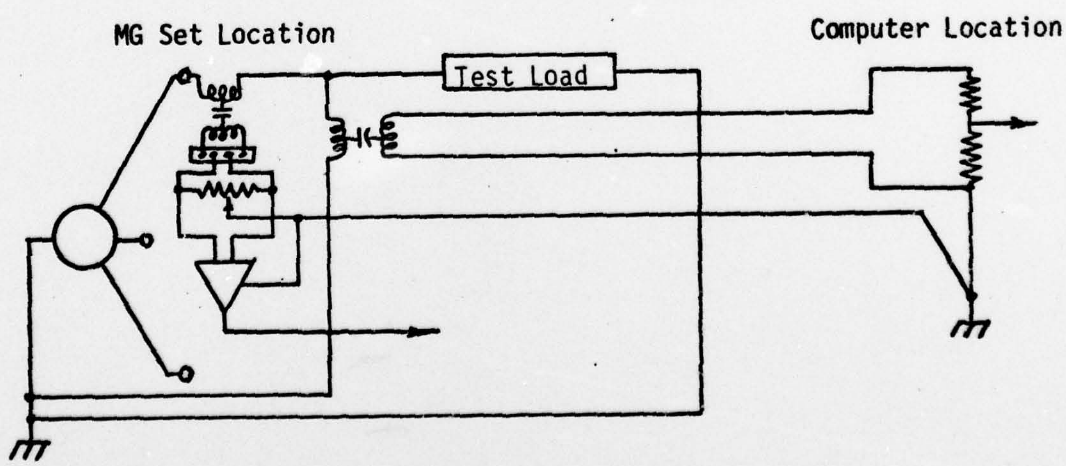


Figure 3. Possible circuit for measurement of the AC voltage and current.

TABLE II. COUPLING CAPACITANCE OF CURRENT AND POTENTIAL TRANSFORMERS WITH EQUIVALENT IMPEDANCE OF THE CAPACITANCE AT 60 HZ. MEASUREMENTS MADE AT 1000 HZ.

Transformer	Capacitance	Equiv. Impedance
Current	109 pF	2400 MΩ
Potential (240V/120V)	400 pF	640 MΩ
Potential (480V/120V)	179 pF	1500 MΩ

THE ENVIRONMENT AND THE INSTALLATION

Introduction

A detailed investigation of the environment and the installation is required to determine which of the previously discussed alternatives should be utilized. Construction of Dearborn Hall and installation of the MG set was completed in 1949. AC and DC lines (many of the AC lines are control lines and consequently are always energized) were run in the same conduit and bundles, resulting in considerable capacitively-coupled, 60 Hz noise voltage appearing in the DC circuits. There is quite a distance between the MG set, the exciter, the starting circuitry, and the control panel. Each has several interconnections with the other elements, and each has many feet of cable on the same cable rack as the others (none of which is shielded)--these are ideal conditions for noise voltages.

It was noted in the previous section that the DC portion of the instrumentation system was anticipated to be more difficult to implement than the AC portion, largely as a result of the isolation provided the AC circuits by the instrument transformers. For this reason much of the investigation focused on the DC circuit. Figure 4 is a simplified schematic of the AC generator and exciter showing the DC measurement points for future reference.

A composite schematic of coupling capacitances and leakage resistances is presented in Figure 5. The ground plane represents experimental ground, to which the machine housings are connected.

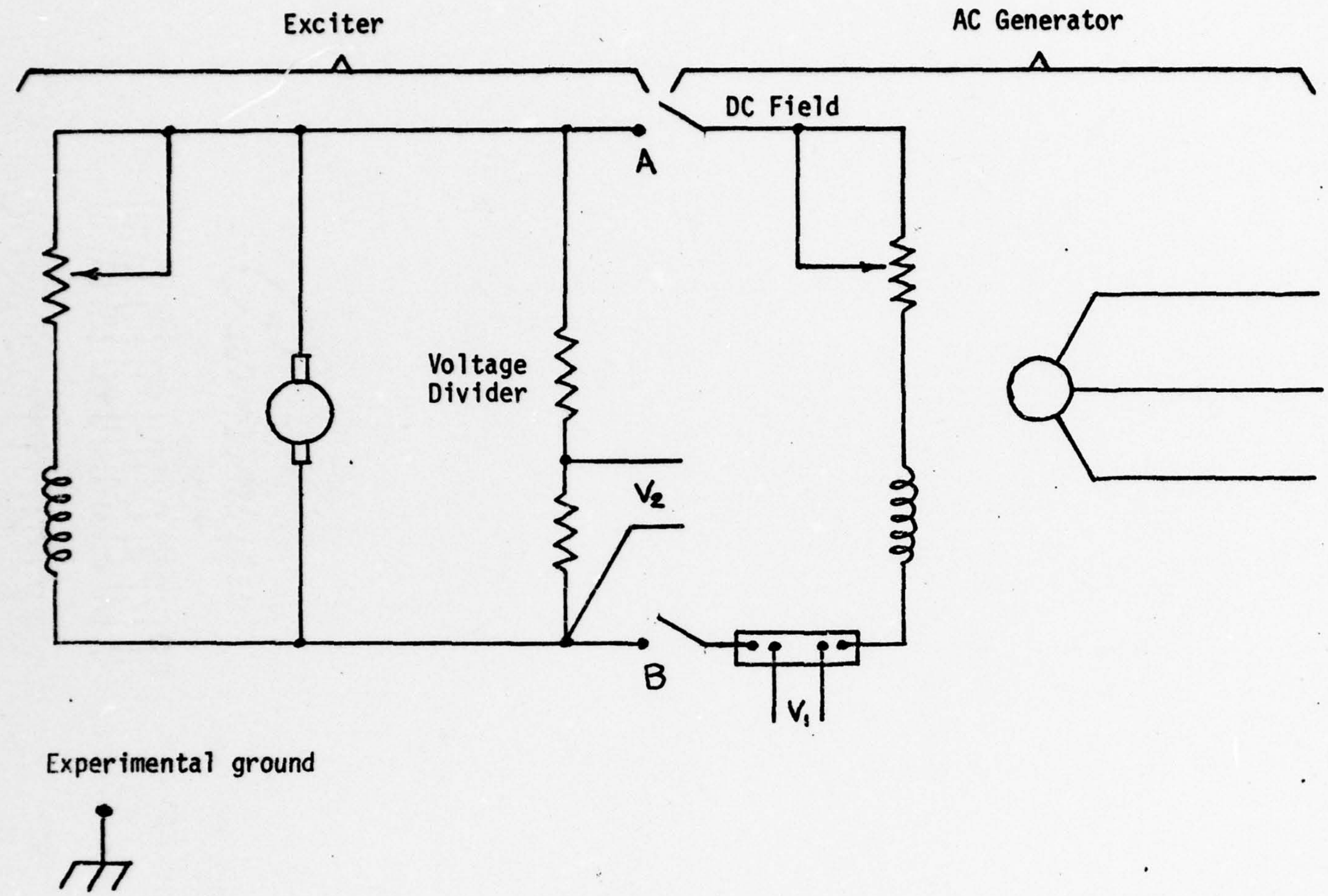


Figure 4. Simplified schematic of the AC generator and exciter showing the DC measurement points.

Capacitors C_1, C_2, C_9, and C_{10} are actually from the windings to the rotor body which, in turn is resistively and capacitively coupled through a thin oil film on the bearings to the housing (experimental ground). The resistors depicted are current leakage paths through various insulating media to the ground plane. Conduit ground is shown separated from experimental ground by some ill-defined impedance. The building was originally constructed with a two-wire convenience system and was later modified to a three-wire, conduit-ground convenience system. Diagrams of the installation do not show how the experimental ground is designed or what is connected into it. As a result, it is extremely unlikely that the conduit ground is at the same potential as experimental ground.

Environmental Noise

(a) 60 Hz noise

Large 60 Hz voltages were measured from points A and B of Figure 4 to experimental ground. These voltages result primarily from the bundling of the AC control lines with the DC lines. Figure 6 is a multiple exposure photograph of the 60 Hz voltages. With the switch closed (see Figure 4) a signal of approximately 12 volts peak to peak is measured. The circuit of Figure 7 (with the x capacitor removed) was used for the measurement. The impedance of 47 pF at 60 Hz is 58 MΩ . In parallel with 1 MΩ resistance this results in an equivalent impedance of essentially 1 MΩ resistance as calculated below.

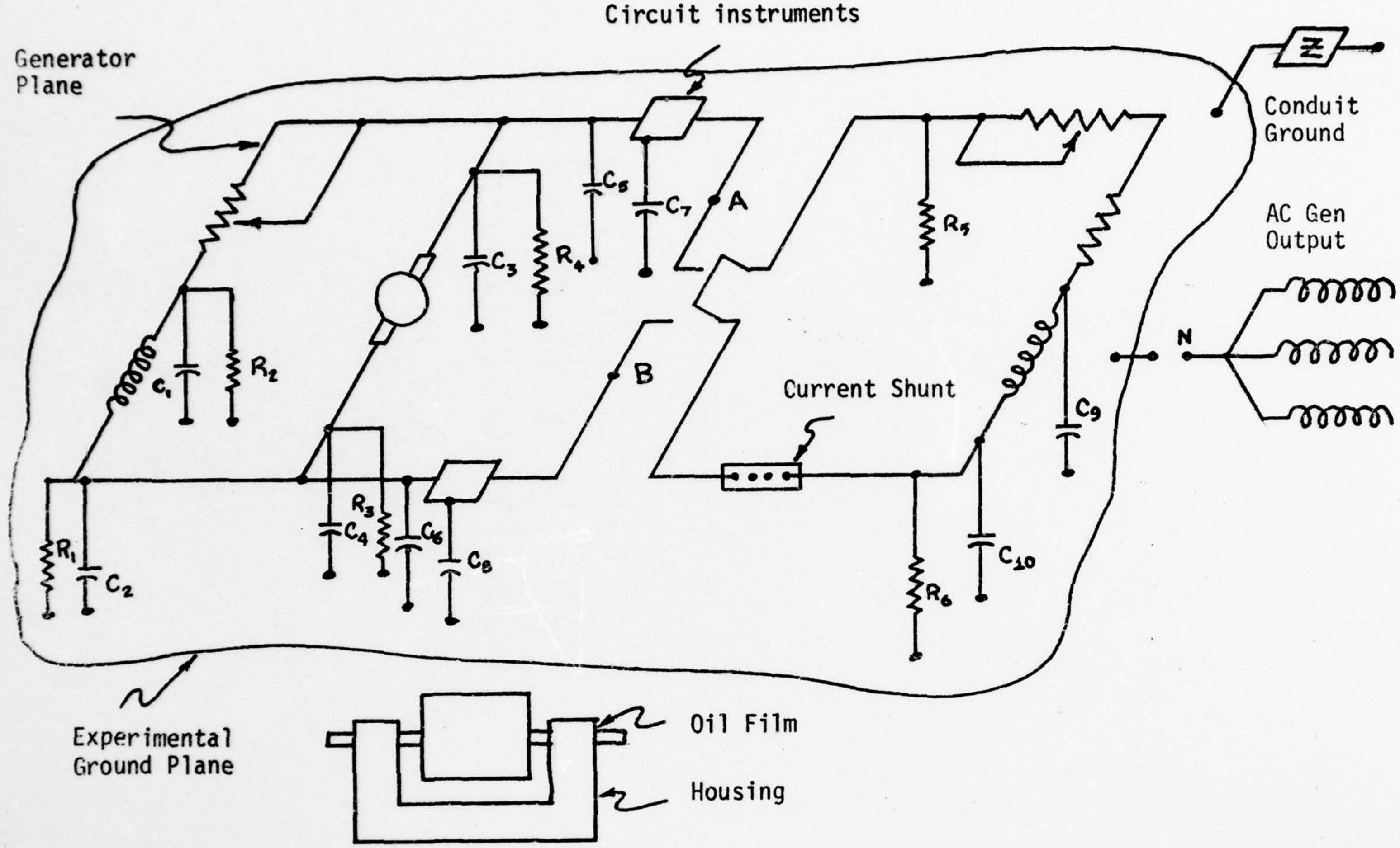


Figure 5. Composite schematic of coupling capacitances and leakage resistances.

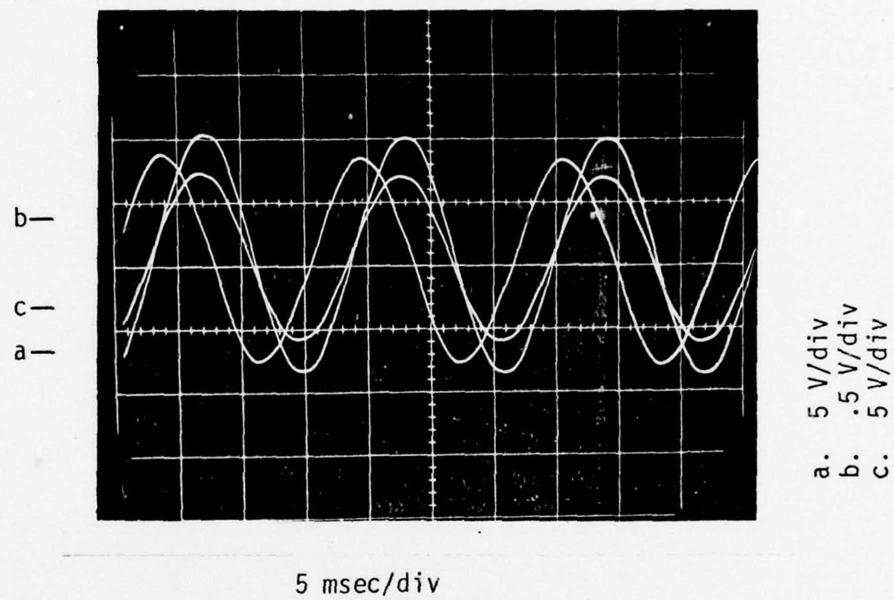
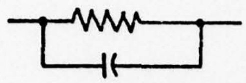


Figure 6. Photograph of 60 Hz capacitively coupled voltages measured from the switch connecting the exciter and the field of the AC generator to experimental ground. (a) is the exciter portion of the circuit with the switch open. (b) is AC generator field portion of the circuit with the switch open. (c) is the complete circuit with the switch closed.

1 MΩ



47pF = 58 MΩ @ 60 Hz

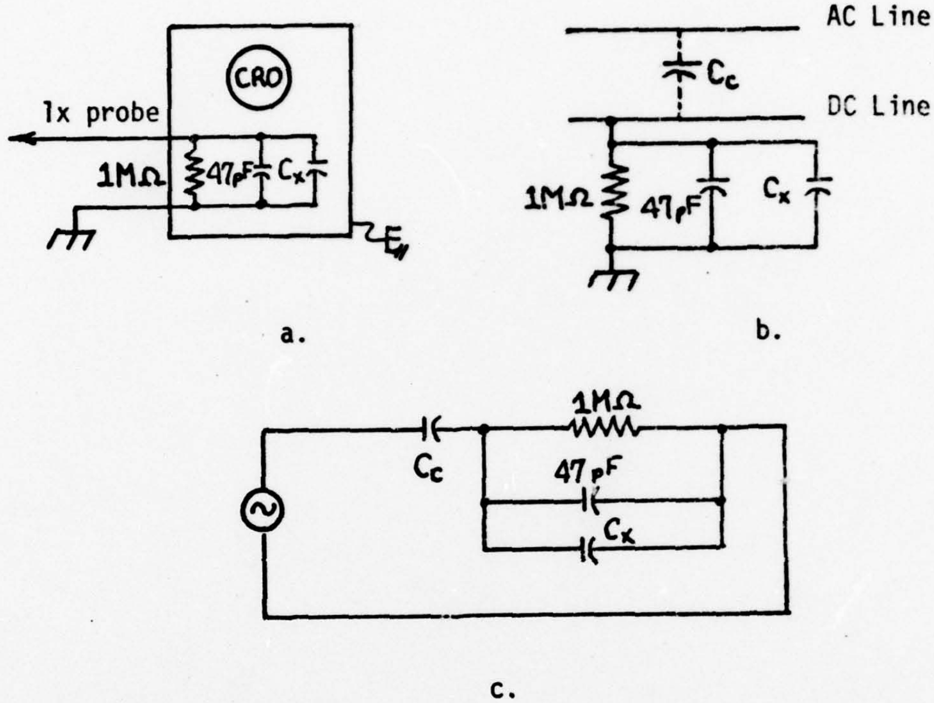
$$z = \frac{X_R\ X_C}{X_R + X_C} = \frac{(1 \text{ X } 10^6)(-j\ 58 \text{ X } 10^6)}{(1 \text{ X } 10^6)+(-j\ 58 \text{ X } 10^6)} = \frac{58 \text{ X } 10^{12} \angle{-90^0}}{58.009 \text{ X } 10^6 \angle{89^0}}$$

$$= .9999 \text{ X } 10^6 \angle{-1^0} \cong 1 \text{ M}\Omega$$

A times ten probe was used with the oscilloscope to determine if the oscilloscope was presenting basically an open circuit to the circuit being investigated. If such were the case, a larger impedance, as in the times ten probe, should yield the same magnitude signal. If any loading of the circuit from the oscilloscope is occurring using the times one probe, a signal of larger magnitude will be observed with the times ten probe. Since the same magnitude of voltage was observed with both probes in the exciter portion of the circuit, and with the switch closed, there is minimal loading with the times one probe. The oscilloscope appears to be an open circuit to the circuit under investigation.

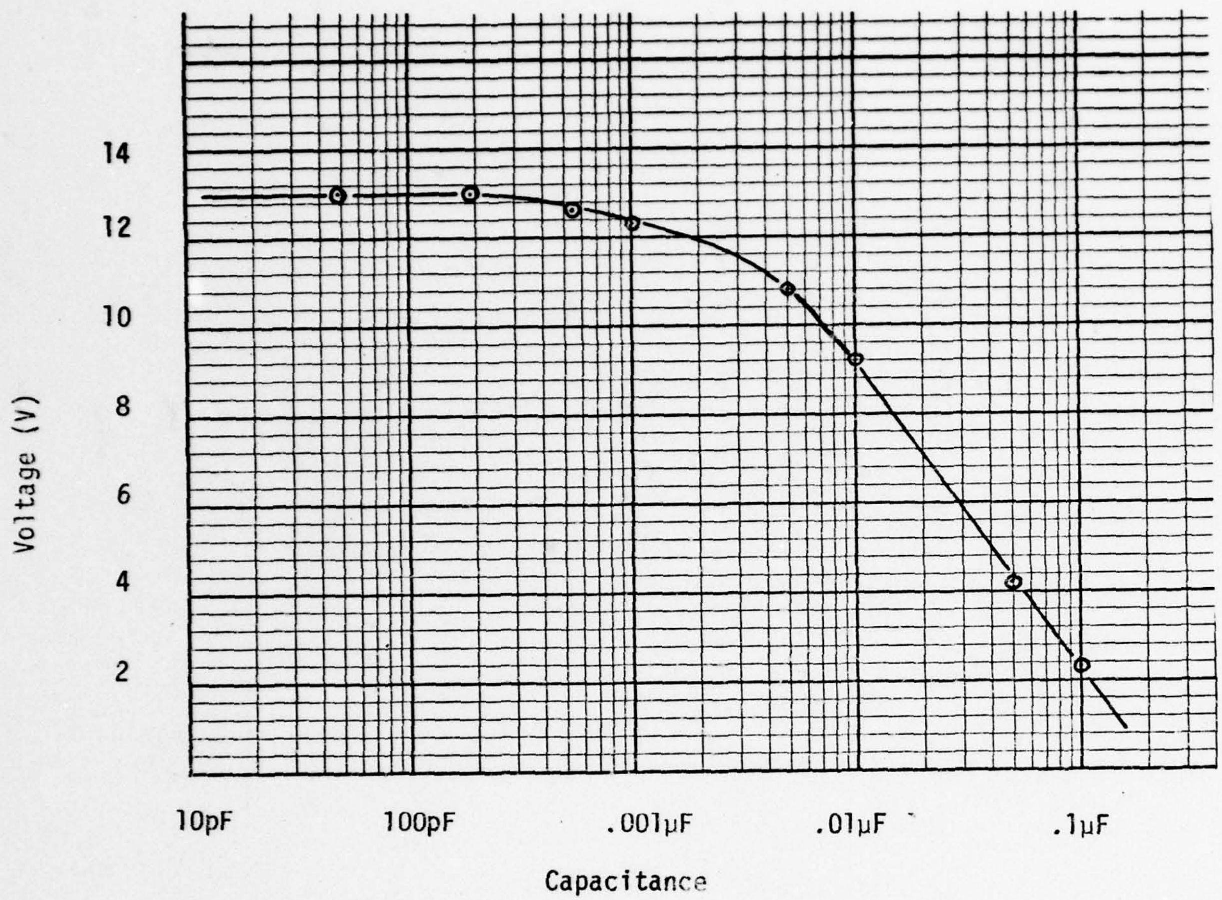
To determine the relative magnitude of the capacitive coupling, a series of capacitors was shunted across the oscilloscope as noted in Figure 7. The results are tabulated and plotted in Figure 8. The equivalent circuit can be diagrammed as shown in Figure 9. The general formula is:

$$V_o = \frac{Z_1 V_s}{Z_x + Z_c} = \frac{V_s \left(\frac{1}{-jwC_x}\right)}{\frac{1}{-jwC_x} + \frac{1}{-jwC_c}} = \frac{\frac{V_s}{C_x}}{\frac{C_x + C_c}{C_x C_c}} = \frac{V_s C_c}{C_x + C_c}$$



Note: $\sim E_{ll}$ means CRO not connected to conduit ground, but is floating.

Figure 7. a. Circuit for determination of relative magnitude of capacitive coupling; b, c. Equivalent circuits.



Value of Capacitor(1)	Volts Measured
47pF	13.0
197pF	13.0
547pF	12.6
.001μF	12.3
.005μF	10.8
.01μF	9.2
.05μF	4.2
.1μF	2.3

(1) Value of C_x in parallel with CRO capacitance (47pF)

Figure 8. Plot of 60 Hz noise voltage measured versus value of capacitance shunted across the oscilloscope.

From the results using the .05 uF capacitor, V_o = 4.2V, V_s = 13V, and C_c is calculated as .0269 uF. Checking at .01 uF capacitance, C_c is calculated as .0242 uF which is within the measurement limitations of the system used. Therefore, the distributed capacitance is approximately .025 uF.

(b) Magnetic Loop Noise.

The circuit of Figure 10 was used to investigate typical magnetic pickup. The wire lengths and runs are shown in Appendix III. As depicted in Table III, the shortest length of cable run exhibited four millivolts peak to peak noise pickup. Since a 50 millivolt shunt has been considered for current measurement, 4 mV of pickup requires that the signal be amplified as soon as it is acquired, and also eliminates the possibility of running low level (mV) signals to the computer for accurate processing.

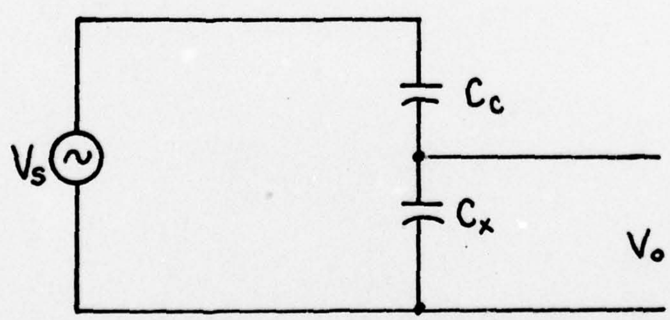


Figure 9. Equivalent circuit of shunted capactior, the coupling capacitance and the noise voltage source.

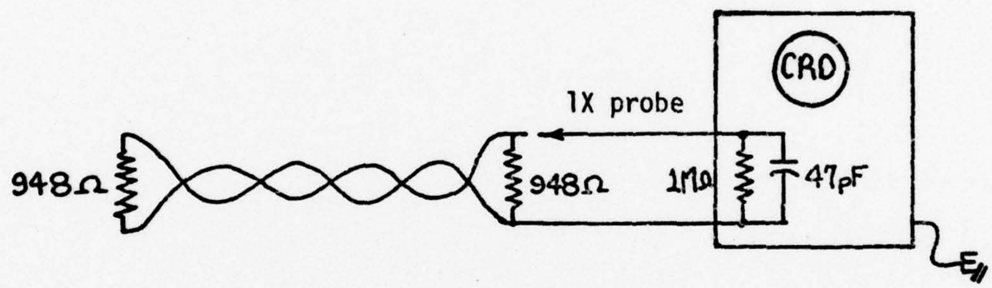


Figure 10. Circuit utilized to measure typical magnetic pickup.

TABLE III. RESULTS OF MAGNETIC PICKUP INVESTIGATION

cable length	type	configuration	pickup
A-135 feet	twisted pair cotton covered	strung out full length	22 mV
B-135 feet	same	one large loop	15 mV
C- 20 feet	same	strung full length	4 mV

(c) Switching Transients.

Voltage transients were measured between A or B and experimental ground when the switch (see Figure 4) was opened or closed. These voltage spikes, measured with the aid of a storage oscilloscope, were in excess of 50 V when the exciter was operating near 125 V. These spikes are the result of the capacitors of Figure 5 charging and discharging as the switch is opened or closed. They appear as a common mode voltage at the DC current shunt. This can seriously damage or destroy any semiconductor devices used to process this signal.

The transients can be reduced to a low level by placing a large capacitor in parallel with a resistor from one side of the switch to experimental ground (a .24 uF, 600V capacitor and a 270 KΩ resistor gave 4V). These transients can be avoided by using proper operating techniques which require that the switch be opened and closed only when the voltage is removed from the exciter. However, in an attempt to reduce stray voltage spikes, the resistor and capacitor were left

connected; since the field circuit remained basically undisturbed by the connection.

(d) Distributed Capacitance and Resistance.

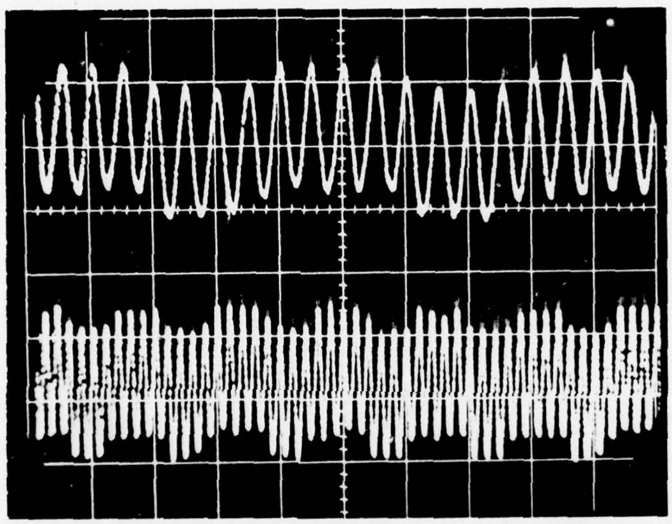
The results of the previous section substantiate the idea that distributed capacitance and resistance similar to that depicted in Figure 5 is present. A logical question to consider is whether or not the capacitance and resistance are balanced (symmetrical) on each line to ground. If they are, the DC voltage from each side of the switch (A and B of Figure 4) to experimental ground should be identical. For these tests, the exciter was operated at 111 volts as indicated by the installed voltmeter (exact accuracy of meter unknown but a representative reading can certainly be obtained). An Electrostatic Voltmeter was used for the measurement. The instrument showed 75 V on one side and 36 V on the other with the switch open. With the switch closed, the instrument indicated 70 V on one side and 41 V on the other. The readings obtained indicated that the resistances in Figure 5 are not symmetrical.

Machine Related Noise

The output of the exciter while running was observed on the oscilloscope in an attempt to identify typical frequencies and levels of noise produced. It produced a high level of noise as shown in Figure 11. The photograph was taken with the oscilloscope connected between A and B (see Figure 4). The magnitude of the signal (10 V p-p) clearly

a—

b—



5 V/div

a. 2 msec/div
b. 5 msec/div

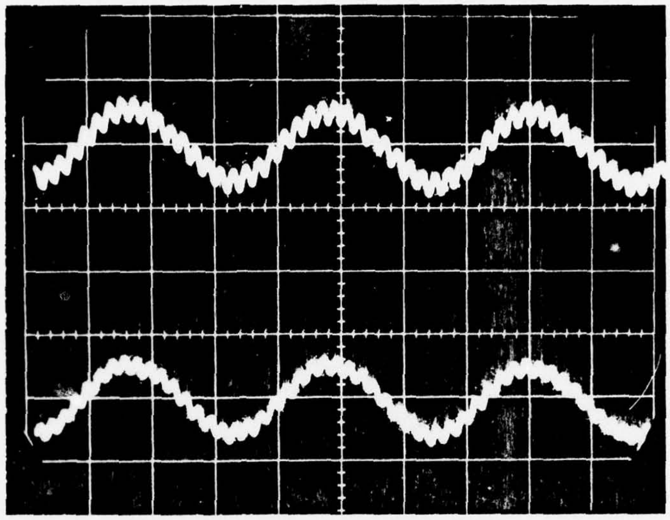
Figure 11. Photograph of exciter output measured from A to B of Figure 4 with the switch open.

indicates that it must be eliminated or at least drastically reduced to allow the acquisition of an accurate signal for the computer.

The output of the exciter was investigated in more detail to determine which frequencies were present by using a General Radio Co. tuned amplifier and null detector. This was done with the exciter under various loads. The primary purpose was to determine if signal frequencies were present in the range of interest (DC to approximately 20 Hz). Frequencies much higher than the frequency of interest can be effectively blocked by the filter, but those close to or below the corner or cutoff frequency of the filter will pass through the filter basically unaltered. The instrument was not capable of measuring frequencies below 20 Hz. Observation indicated a low frequency signal (10 Hz or less), but the amplitude was negligible compared to those of 20 Hz or greater. The frequencies found are tabulated in Appendix IV. A very strong frequency of approximately 955 Hz (frequency varied slightly with exciter loading) was noted, but it is far enough removed from 20 Hz to be effectively filtered. The frequency is suspected to be tooth ripple from the exciter. Strong frequencies of approximately 30 and 60 Hz were also noted. Since these signals are so close to the corner frequency that they cannot be effectively filtered, they will certainly degrade the quality of the DC signals presented to the computer. Either this error must be accepted or a machine which develops no internal low frequencies must be located and installed.

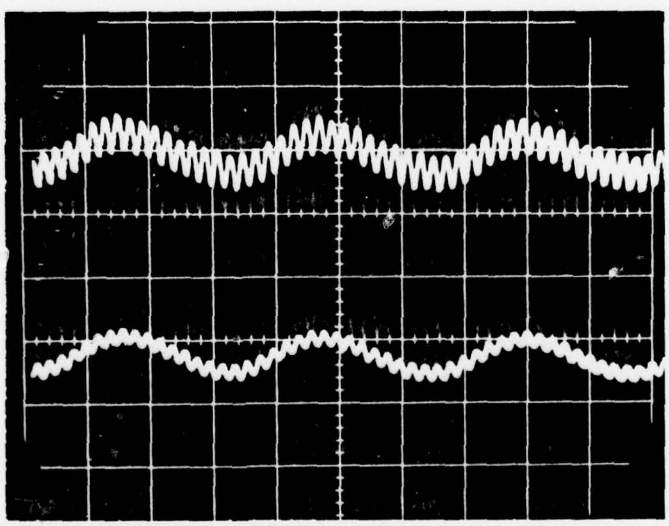
Subsequent measurements from A and B to experimental ground (see Figure 4) are recorded in the photographs of Figure 12. This is of

interest since the measurement of Figure 11 was taken across the switch (A to B) rather than from one side of the switch to experimental ground. Neglecting distributed capacitance, there should be no tooth ripple signal observed. The presence of a signal is explained, however, by the presence of coupling capacitance as noted in Figure 13. The tooth ripple is riding on top of the 60 Hz capacitively coupled wave.



20 V/div

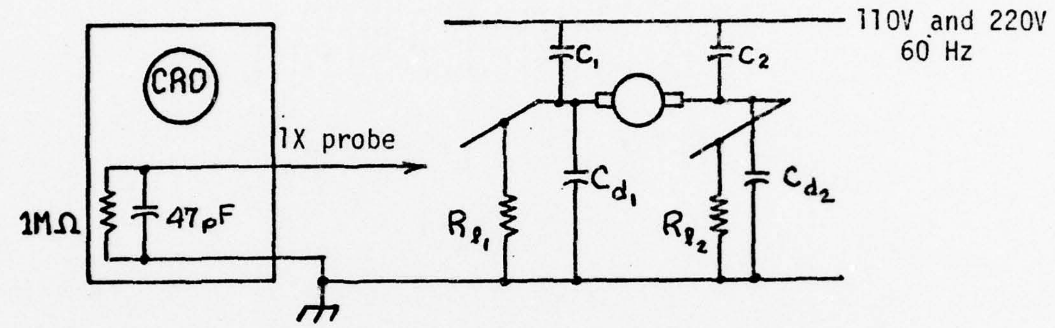
5 msec/div
a.



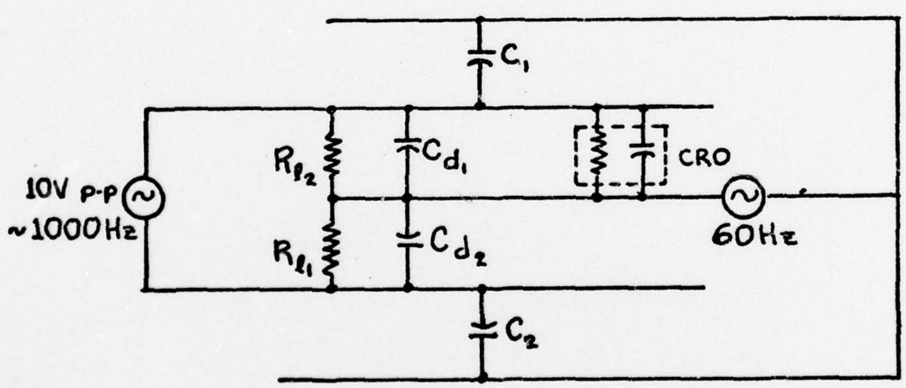
20 V/div

5 msec/div
b.

Figure 12. Photograph of capacitively coupled tooth ripple. (a) is with the switch connecting the exciter and the AC field closed. (b) is with the switch open. Both (a) and (b) contain a signal from each side (A and B of Figure 4) of the switch.



a.



b.

Figure 13. a. Diagram of measurement circuit of capacitively coupled exciter voltage. b. Equivalent circuit.

INSTRUMENTATION AMPLIFIERS

General

With a fixed installation, there can be a problem of inaccessible wiring. The circuit schematic may be available to diagram connections on paper, but the actual circuit may be located under the floor, in conduits, heavily bundled with other wires, etc. The installation usually cannot be altered in any permanent manner without considerable cost, document changing, and approval gathering. With these restrictions a reality, the DC ammeter of the AC generator field was chosen as a signal pickup point for initial testing of components and arrangements of components since connection to the ammeter was relatively easy.

Use of the 50 mV shunts necessitates the amplification of the signal for the computer use. Since there are many shunts requiring signal amplification, this section will be devoted to amplification systems. The previous section has indicated that the signal environment is one of high magnetic and electric noise levels and common mode voltages. Thus, common mode rejection and noise immunity become prime considerations for the amplification systems.

From preliminary discussion and reading, and from tests run, a circuit such as Figure 14 appeared desirable for the following reasons: (1) boosting the signal immediately after pickup would reduce the effect of the noise picked up in the transmission line on the final signal, and common mode voltages would be largely rejected; (2) running

a twisted pair of leads (or pairs if needed) would minimize magnetic loop noise pickup; (3) the shielding (while only relatively effective unless solid and double layered) would help reduce electric noise pickup; (4) the buffer placed prior to the filter would provide a low loop impedance to also help minimize noise pickup; (5) the filter placed immediately prior to the multiplexer should reduce if not eliminate noise of a higher frequency than that of interest; (6) loading the line immediately after the filter should provide a stable signal for the sample and hold amplifier.

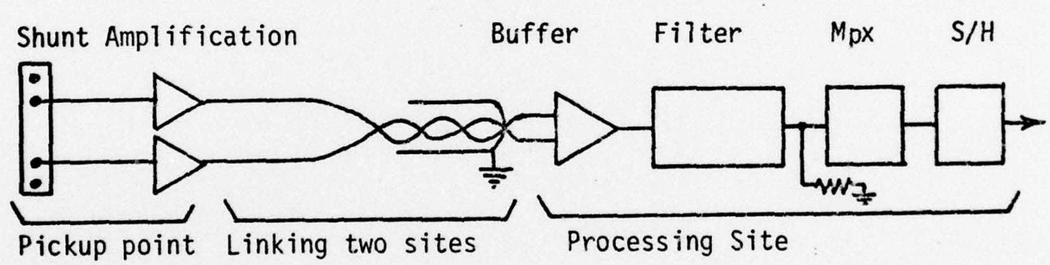


Figure 14. Block diagram of a desirable system to provide a quality signal to the sample and hold amplifier.

Since there are multiple signals of higher frequency than that of interest and since they are of considerable magnitude, the decision was made to purchase a variable cutoff, active filter. Inherent problems with precision component matching as well as stray capacitances and leakages made the fabrication of a variable filter with specifications that matched the commercially available models economically impossible. A

Datel Systems, Inc. active resistor-tuned four pole Butterworth filter was chosen. The specifications and connections for the filter are in Appendix II.

Instrumentation Amplifiers (Fabricated)

(a) General.

A differential input, differential output amplification system must be utilized in order to run a pair of twisted signal leads. The system outlined for this purpose in most reference books is that of Figure 15a. When this is combined with a buffer amplifier as in Figure 15b, the system is referred to as an instrumentation amplifier. The common mode rejection (CMR) of such a system is dependent on the close matching of the resistors. Theoretically, it has a CMR of 60 dB with .1% matching of the resistors and up to 100 dB of CMR with trimming of the resistors. However, any gain of the differential amplifiers reduces the CMR of the entire system by that amount.

Another highly recommended instrumentation amplification system is that of Figure 16. This also depends on the matching of the resistors for CMR, but it is designed such that the power supply for op amps A_1 and A_2 floats with the common mode voltage, thereby removing the common mode voltage from the input amplifiers. Again, the overall CMR is reduced by any gain of the differential amplifiers.

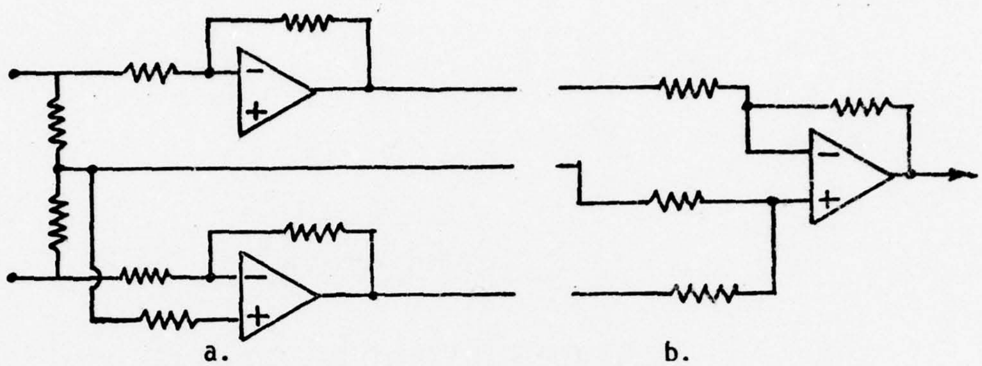


Figure 15. Buffer amplifier combined with a differential input, differential output amplification system to form an instrumentation amplifier.

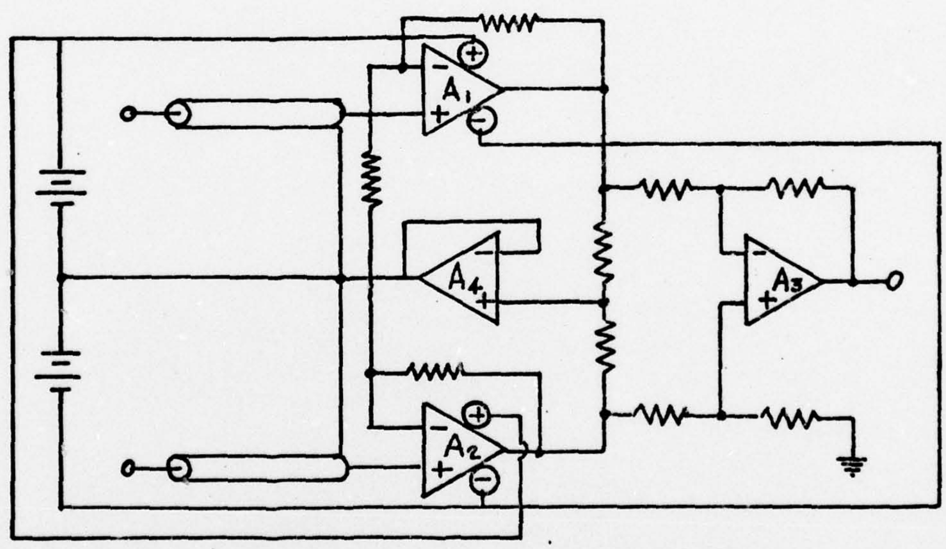


Figure 16. An instrumentation amplifier with the power supply floating with the common mode voltage.

(b) Testing and Evaluation.

The circuit of Figure 15 was used with two different type amplifiers, the Archer dual 741 and the National Semiconductor LM 324N. Testing in controlled conditions was used to check the CMR of each setup. If the CMR is low, the circuit cannot be considered for use in the measurement system due to the presence of high common mode voltages. A function generator was used to provide an identical signal to the inputs of both sides of the instrumentation amplifier. A consolidation of the results is in Table IV.

In all cases tested, CMR is partially dependent on well matched resistors. All resistors were matched with a Fluke 8100A digital multimeter which gives four place accuracy with an error of plus or minus one in the last place. This is easily within the .1% tolerance limit mentioned earlier for 60 dB CMR. With the circuit of Figure 15, 40 dB of CMR was lost due to a gain of 100 on the differential amplifiers. The systems functioned properly in all cases giving a representative DC voltage reading, but the CMR is unsatisfactory for the needs of the measurement system.

In addition to the unsatisfactory CMR of the circuit in Figure 16, op amp A_4 must be driven by a separate power supply from that of op amps A_1 and A_2. This would require several more runs of cable if the differential amplifiers were set at the pickup point and the buffer at the process point. The added cabling makes this impractical; since there are several measurement points in the total system.

TABLE IV. RESULTS OF CMR TESTS ON FABRICATED INSTRUMENTATION AMPLIFIER CIRCUITS. ALL MEASUREMENTS ARE PEAK TO PEAK. INPUT WAS A SINE WAVE OF 3.5 HZ.

circuit	input	output	CMR (dB)
Archer 741 Figure 15	80 mV	15 mV	8.6
LM 324N Figure 15	40 mV	2 mV with spikes, 24 mV	26.0
	90 mV	3.5 mV with spikes, 16 mV	28.0 15.0
	.25 V	5 mV with spikes, 8 mV	34.0 29.9
LM 324N Figure 16	40 mV	2 mV	26.0
	90 mV	1 mV with spikes, 1.5 mV	39.1 29.5
	.15 V	2 mV with spikes, 20 mV	37.5 17.5
	1 V	2 mV with spikes, 40 mV	54.0 28.0

The spikes on the signal referenced in Table IV appear to result from distributed capacitances in the layout, since they turn to pure oscillations as the test frequency is increased to the 300 to 500 Hz range.

(c) Summary.

Since 50 mV shunts are being used at several measurement points, and since the magnetic pickup of a 20 foot section of twisted pair leads was 4 mV, it is imperative that the signal be amplified immediately after acquisition. This would make the signal to noise pickup ratio greater by a factor equal to the amplification. Several recommended instrumentation amplifiers were fabricated which were capable of amplifying the signal to plus or minus 10 volts. However, the CMR of the fabricated systems was incapable of rejecting the common mode voltages present. In addition, the fabricated systems exhibited considerable stray capacitances due to excessive lead lengths and poor lead positioning, a result minimized by commercial miniaturization processes. At this point the logical alternative available to present a quality signal to the multiplexer with an op amp system was to obtain and test the commercially produced instrumentation amplifier.

Instrumentation Amplifiers (Manufactured)

The Analog Devices Integrated Circuit Precision Instrumentation Amplifier, AD 521J, was purchased as a typical instrumentation amplifier to explore the characteristics and the possibility for use of instrumentation amplifiers. The specifications as listed by the manufacturer and the specific connections made to the amplifier are in Appendix V. A combination of resistors was used which resulted in a gain of approximately 100.

To test the common mode rejection of the amplifier, a sine wave from a function generator was fed into both inputs and the output was measured. A signal output of .1 mV was measured when 500 mV was applied to the inputs. This was constant over a frequency range of DC to 3000 Hz. These figures indicate a CMR of 75 dB. Since the gain was 100, another 40 dB of CMR must be added for a total of 114 dB of CMR.

The function generator was used to feed a signal into one input terminal of the amplifier while the other was held to common. The output signal was found to be quite clean and of the correct amplitude over a wide range of frequencies and amplitudes (within the capabilities listed on the specification sheet).

Input Protection for Amplifiers

Most manufactured amplifiers have provisions for input protection for common mode or differential voltages (depending on which mode of amplification is used) equal to or less than the power supply voltage. However, voltage signals in excess of the power supply voltage will damage the amplifier. Consequently, protection against such voltages must be provided.

The voltages in the AC generation system are extremely high compared to the voltage that will be tolerated by any amplifier. Voltage spikes in excess of 50 V in the DC circuit have been observed. Even though this particular voltage has been observed and reduced, with the

high voltages and coupling capacitances present, the likelihood of other stray voltage spikes of equal or greater magnitude is strong. A protective circuit such as that shown in Figure 17 should be utilized on all active devices where there is any possibility of accidental or momentary excessive voltages. Since the input impedance of most instrumentation amplifiers is 10^8 to $10^{10}\Omega$, the added resistance will not affect the accuracy of the system. If excessive common mode voltages do occur, the system will not function accurately during the excessive voltages. However, if the protection is not provided, rather than data being momentarily inaccurate, the device will be destroyed.

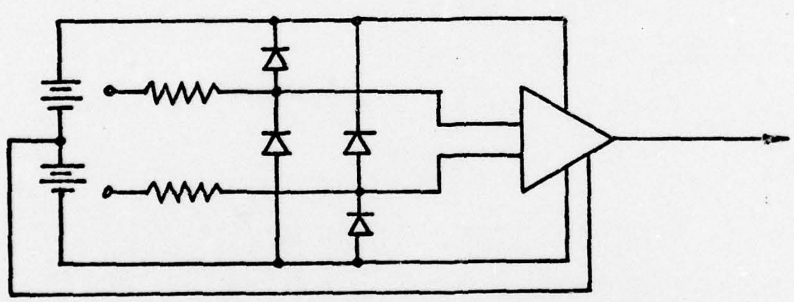


Figure 17. Circuit to protect instrumentation amplifiers from excessive common mode voltages.

THE INSTRUMENTATION SYSTEM

Measurement of AC Generator Field Current and AC Field Terminal Voltage

A 50 mV, 10 amp shunt was installed in the AC generator field circuit to provide a voltage signal for measurement (see Figure 4). Measurements taken from the shunt showed a common mode voltage of 13 V p-p at 60 Hz and a 10 V p-p tooth ripple. When the 270 K resistor in parallel with the .24 uF capacitor was placed from A (Figure 4) to experimental ground, the common mode 60 Hz signal dropped to 2 V p-p while the tooth ripple dropped to 1 V p-p. Measurements of the voltage signal at the shunt output terminals showed there was 20 mV p-p of noise on a DC signal of 50 mV. Noise of a higher amplitude (about 30 mV p-p) cycles through the signal with the same frequencies as those noted from the investigation of the inherent exciter frequencies. The noise decreases slightly as the AC generator field current is decreased, but definitely not linearly with the signal level.

To determine if the noise voltages were common mode voltages, the oscilloscope was used in the differential mode which means that common mode voltages are removed from the displayed signal. The only noise voltage which remained was the noise picked up and/or generated by the oscilloscope and the probes. The DC signal was displayed clearly. This indicated that the noise on the signal was common to both output terminals of the shunt.

The foregoing measurements indicate that the DC current measurement circuit will require an amplifier in the differential mode as

depicted in Figure 2c. An AD 521J instrumentation amplifier was placed in the circuit as shown in Figure 18. A Datel filter was added with a cutoff frequency of 30 Hz. The resulting signal output from the filter was within the .1% error limitations desired. It should be noted that this system was left floating and was not tied to experimental ground.

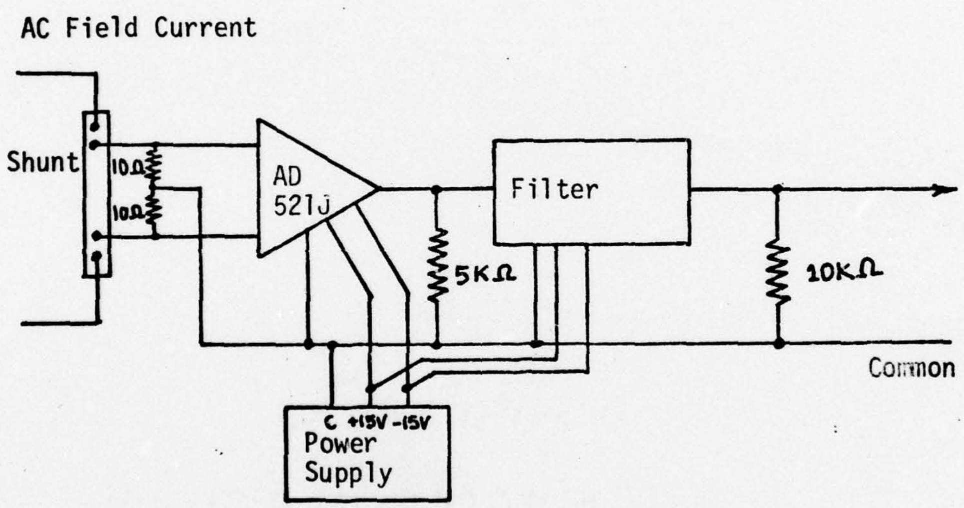


Figure 18. AC field current measurement circuit using AD 521J instrumentation amplifier.

The need for input protection for the amplifiers was reinforced when after some testing, the AD 521J was suddenly rendered inoperable. There is no way the exact cause can be determined, but as discussed earlier, it is possible that a large stray voltage spike appeared in the circuit. Without the protection suggested in Figure 17, the amplifier was destroyed.

Terminals were added across the switch connecting the AC generator field and the exciter. The signal from the exciter has several component frequencies present as noted in a previous section. A voltage divider was developed for use to divide the voltage down to the allowable ± 10 V. The divider was set up for 150 V maximum across the terminals. The divider values were 47.42 KΩ and 3.383 KΩ or a ratio of 14:1.

The divider was connected directly to a Datel filter and the output was observed. With the exciter voltage and current at 120 V and 40 amps (maximum rated), the filter output indicated a correct DC voltage of 8 V, but fluctuated ± 7 mV. The fluctuations appeared to be of the same frequencies as those found in the investigation of the inherent exciter frequencies. Even with the ± 7 mV fluctuations, the 8 V reading (resulting from 120 V on the exciter) has an error of less than .1%.

However, since an amplifier in the differential mode is required for the current measurement circuit, an amplifier in the differential mode will also be required at the voltage divider to eliminate ground loop current problems and to avoid upsetting the voltage divider ratio. The recommended circuit is shown in Figure 2c.

Measurement of AC Voltage and Current

Extensive modification at the AC generator will be required before observation and examination of the AC signal can be accomplished. There is no convenient point where the transformers can be connected

into the system. The modification was postponed until a complete proposed system is accepted. The machines will be adapted at that time.

However, from environmental studies conducted and from previous discussions, the system shown in Figure 19 is recommended. Utilizing separate common lines for the potential transformers allows a twisted pair to be run for all signals. This will reduce loop pickup on the voltage signals. Placing the voltage divider of the AC voltage circuit at the computer will divide the noise voltage as well as the signal voltage. Utilizing a "star tree" or "radial" type ground connection will minimize the signal interactions on the common line. "Radial" or "star tree" distribution or connection implies that each signal has its own line and does not share a line or any portion of a line with another signal. This system is accomplished if all lines which must be connected together are all connected at a mutual point. This distribution rule should be observed whenever possible, whether power lines, signal lines, or ground lines are being considered.

Amplifiers in the differential mode are shown connected to the current shunts. The noisy environment and unbalance caused from lead dress, as noted for the DC current measurement, will not permit accurate representation of the current with single-ended amplifiers. Also, as already mentioned, single-ended, integrated circuit amplifiers are not readily available.

Filters are shown at the computer locations. Again, due to the noisy environment, they will be required to filter out those noise voltages which have a higher frequency that that of interest (approximately 120 Hz).

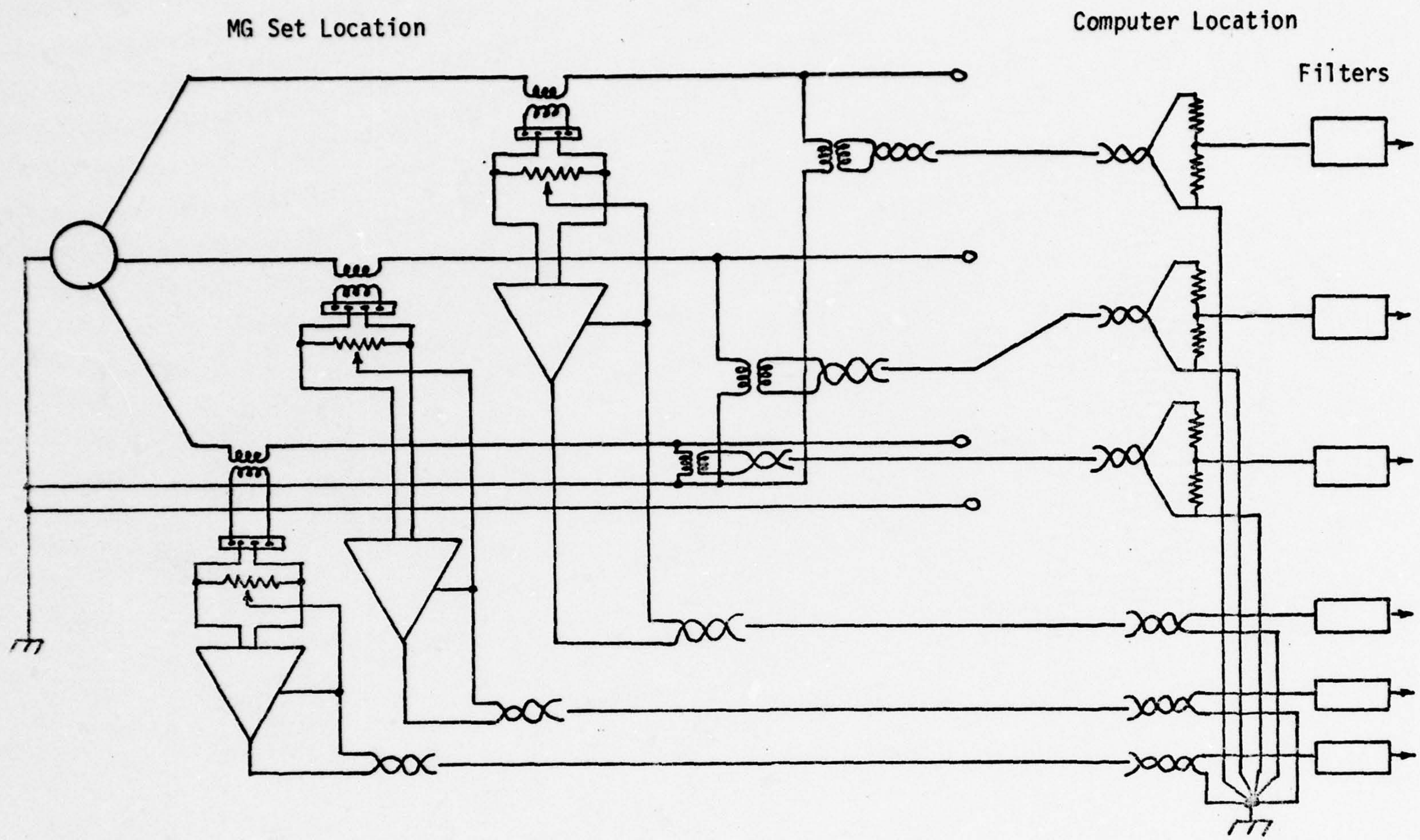


Figure 19. Recommended measurement circuit for the AC signals.

SYSTEM COMPONENT SPECIFICATIONS

General

A general rule applied in writing specifications is to require each tolerance to be restricted by a factor of 10, where possible, over the total tolerance or error desired. In most instances, this will be sufficient to meet the desired overall criteria when the individual error terms are summed.

Power Supplies

Two options for selecting power supplies are available. Either one large power supply can be chosen, which will require leads to every component requiring power, or several smaller supplies can be chosen to provide power for each subsection. Of course, any combination between the two extremes is also possible. Due to the distances between pickup points, and between pickup points and the computer, several smaller supplies are desired, which could be located where required. The use of several smaller supplies also eliminates the possibility of signal interactions and power supply disturbances unless the signals are already connected on a common bus. In the latter case, if practicable, a single supply could provide power for all components on the bus line. Again, however, the "star tree" distribution should be maintained as nearly pure as possible.

These considerations imply that power supplies as listed in

Table V are desired. The rating of each supply is dependent on the amplifiers and the filters chosen for the circuit.

TABLE V. LISTING OF POWER SUPPLIES DESIRED AND UTILIZATION OF EACH.

Total	Individual Utilization
1	for the three filters of the AC voltage signals (the commons are already connected in these voltage signals).
3	one for each AC current signal to provide power for the amplifier and filter of each circuit.
1	for the DC current signal amplifier and its filter.
1	for the DC voltage signal amplifier and its filter.

Amplifiers

Since a ±15 mV noise signal was noted on the 50 mV current shunt signal and since an error of .1% is desired (.01% with the specification guideline) the noise must be reduced to .05 mV (.005 mV). Using .005 mV as the most restrictive tolerance requires that the common mode rejection (CMR) of the amplifier be 69.5 dB at a gain of one for the amplifier. Since a gain of 200 is required using the 50 mV current shunt, 46 dB of CMR must be added which makes the total CMR required equal to 115 dB.

Another important specification for this application of the amplifier is the slew rate (the rate at which the amplifier will respond from 0 to full scale rating). Since step-like changes will be applied

to the AC system, the slew rate required of the amplifiers could be quite fast. However, observation of data from similar disturbances indicates that a slew rate of 10 mV/usec will be required for the AC voltage and 2 mV/usec for the DC voltage. These slew rates are easily obtainable according to the specification tables of several instrumentation amplifiers. The slew rates required for the currents of both systems will be less than the voltages. Since the voltage slew rates are easily obtainable, they should be applied to the currents also.

Two additional specifications which are important are linearity and internal noise. Linearity will be important as the resulting signals from the disturbances may have a considerable range. Internal noise is important since it is added to the output signal. Each, individually, should not exceed the .01% tolerance limit.

Temperature variations should not be critical as the temperature is controllable and normally would not vary more than 10^{o} F without control. However, the temperature variation must also remain within the .01% tolerance limit.

Filters

Two of the main low pass filter types are the Butterworth and the Bessel Filter. The Butterworth is more accurate if f_c, the cutoff frequency, is close to the frequency of interest. The response curve remains linear much closer to f_c than with the Bessel filter. If a step response is anticipated and accurate data of that response is

required, then the Bessel filter should be used. The Butterworth filter has an overshoot response to the step input while the Bessel does not overshoot and retains an almost equivalent slew rate. Both type filters produce a considerable phase shift which generally increases as the number of poles increases. Also, the phase shift of the Butterworth filter is greater than the phase shift of the Bessel filter. The signal of interest will determine which filter should be utilized.

A required feature for all filters in this instrumentation system is that they have a variable cutoff. This cutoff should range from DC to 500 Hz (about 10 times the highest frequency of interest).

The filters for the DC circuit should have steep cutoff slopes (4 pole minimum) as the signals of interest are close to several frequencies inherent in the machines. This factor also indicates that the Butterworth filter should be used to obtain a more accurate signal output.

Since step-like disturbances are to be applied to the AC portion of the circuit, a step-like response could be anticipated. The Bessel filters should be utilized in the AC portion of the circuit since they have a superior step input response curve.

The specifications for all filters should meet the .01% error tolerance individually in order to keep the total error budget for the system within the .1% desired.

CONCLUSION

The analysis of the environment, the major equipment, and several measurement circuits has provided criteria for the instrumentation of a measurement system for the AC generator. The criteria provide guidelines for the selection of equipment to be utilized in the measurement system and for the placement and connection of that equipment.

The environment definitely can be categorized as noisy, composed of relatively high electric and magnetic noise levels which will hinder the acquisition of accurate sampled signals. A considerable amount of power lead coupling capacitance and machine leakage resistance causes numerous and sometimes unexpected problems such as unbalanced voltages and voltage spikes when switches are closed. As a result, over-voltage protection must be provided for any element which has an integrated circuit and which interfaces directly with the machine circuits. The amount of magnetic noise pickup will require that twisted pair leads be run where possible. In addition, all low level (mV) signals will have to be amplified as soon as they are acquired to minimize the effect of the magnetic pickup on the signal voltage. All voltage divider networks should be placed at the termination of the transmission of any high level voltage signal to improve the signal to noise ratio.

Since truly single-ended amplification systems are not readily available, several instrumentation amplifiers will be required. The unsuccessful attempt to fabricate these amplifiers with an adequate CMR implies that amplifiers will have to be purchased. Specifications

for the instrumentation amplifiers have been discussed.

The high level of noise picked up and also generated by the exciter indicates that variable cutoff filters are desirable for all signal circuits and should be placed in the circuit immediately prior to the computer terminal. The filters in the DC portion of the system will need to be multiple pole (4 pole minimum) Butterworth filters while those in the AC portion should be Bessel filters.

Multiple power supplies are recommended to reduce the possible ground loop signal interactions. In addition, convenience of connection will be achieved and numerous additional lengths of lead cable will be eliminated.

All of the purchased component (amplifiers, filters, etc.) specifications should individually remain within the .01% error criterion. The noise levels present will make the error budget critical. It may not be physically possible to find components which will keep the total error budget within the .1% desired. This will depend on the economic constraints imposed for the development and construction of the measurement system.

Before the project can be continued, considerable modification of the AC distribution system of the AC generator will be required to accept the instrumentation transformers and the test leads.

BIBLIOGRAPHY

1. Basu , R. N., 1970. Measurement of Small Signals in a Noisy Environment. Electrical Interference in Instrumentation. Institution of Electrical Engineers, 1970.

2. Bull, J. H., 1970. Interference to Instrumentation Due to Transients in the Supply System. Electrical Interference in Instrumentation. Institution of Electrical Engineers, 1970.

3. Coram, R. W., and G. A. Jackson, 1970. Electrical Interference in Instrumentation: Modern Measuring Techniques. Electrical Interference in Instrumentation. Institution of Electrical Engineers, 1970.

4. Fernando, C. E., 1970. Measurement of Low Level Signals in a High Power Synthetic Test Circuit. Electrical Interference in Instrumentation. Institution of Electrical Engineers, 1970.

5. Graeme, Gerald G., 1973. Applications of Operational Amplifiers: Third Generation Techniques. McGraw Hill Book Company.

6. Greenwood, P., 1970. Current and Voltage Measuring System on an EHV Circuit Breaker Test Facility. Electrical Interference in Instrumentation. Institution of Electrical Engineers, 1970.

7. Millman, Jacob,and Christos C. Halkias, 1972. Integrated Electronics. McGraw Hill Book Company.

8. Spitzer, Frank, and Barry Howarth, 1972. Principles of Modern Instrumentation. Holt, Rinehart, and Winston.

9. Analog-Digital Conversion Handbook, 1972. Analog Devices, Norwood, Massachusetts.

10. Applications Manual for Operational Amplifiers, 1968. Engineering staff of Philbrick/Nexus Research.

11. Linear Applications, 1972. National Semiconductor Corporation.

12. Handbook of Operational Amplifier Applications, 1963. Applications Engineering Section of Burr Brown Research Corporation.

13. General Applications discussion of following catalogs: Analog Devices; Burr Brown; Datel Systems, Inc.

APPENDICES

APPENDIX I

Definitions

1. Experimental ground

2. Common of the immediate circuit

3. Micro u

APPENDIX II

FILTER CONNECTIONS AND SPECIFICATIONS

ACTIVE FILTER SPECIFICATIONS (typical @ 25°C, ±15VDC, rated load unless otherwise noted)

Model Number (see ordering information)	FLT-BP4B	FLT-LP4	FLT-LP6
Filter Type	Band Pass	Low Pass	Low Pass
Number of poles (same as number of equal tuning resistors required)	4 poles (2 pole-pairs)	4 poles	6 poles
Response Characteristic and Q (selectivity) (see ordering information)	Butterworth only $Q = 5$ or 10 (±10% tol.)	Butterworth *or Bessel*	Butterworth *or Bessel*
Tuning Resistor Formula (all tuning resistors are equal for a given filter, one resistor per pole required)	$R\,(K\Omega)=2\left[\frac{f_o\,(max)}{f_o}-1\right]$	$R\,(k\Omega)=2\left[\frac{f_c\,(max)}{f_c}-1\right]$	
Pass Band Gain (band pass) or DC Gain (low pass)	0 ±0.3dB[1]	0 ±0.02dB	
Cutoff Frequency Tuning Range (All low pass filters have essentially unity gain from DC up to 1/10 of selected f_c.)	0.05 to 50Hz 0.5 to 500Hz 20 to 20KHz	*50:1 tuning ratio* normal[2]: 1 to 50Hz; 10 to 500Hz; 100 to 5KHz; 1K to 50KHz extended[2]: 0.1 to 50Hz; 1 to 500Hz; 10 to 5KHz; 100 to 50KHz	
Accuracy and Drift of f_c or f_o	≤ ±3% ±0.03/°C (Using 1% 100ppm/°C tuning resistors)	≤ ±3% ±0.05%/°C (Using 1%, 100ppm/°C tuning resistors)	
INPUT CHARACTERISTICS			
Input Voltage Range (single-ended)	±10V min.		
Input Impedance	100K Ohms		10^9 Ohms
Initial Offset Voltage	±2mV (Adj. to zero using external trimpot)		
Offset Voltage Drift (0 to 70°C)	±20μV/°C	±50μV/°C	±75μV/°C
Input Bias Current	NA[3]	10nA	
OUTPUT CHARACTERISTICS			
Rated Output Voltage	±10V		
Rated Output Current	2mA (short circuit protected to ground)		
Output Impedance	1 Ohm		
Output Noise	50μVRMS (1Hz to 100KHz)	75μVRMS (1Hz to 50KHz)	

POWER SUPPLY			
Voltage (rated specs)	±15VDC		
(operating)	±6 to ± 18VDC	±12 to ±18VDC	
Current, Quiescent	16mA	22mA	28mA
Temperature Range			
Operating	0 to +70°C		
Storage	-55 to +125°C		
Case Style	A (50Hz model) C (500Hz & 20KHz models)	B	A (50Hz models) B (all other models)
Socket	MS-12, $5.00		

NOTES

1. The gain of the band pass models may be externally adjustable from 0 to +10.
   See external connections diagram.
2. All models may be operated in the extended frequency ranges. Anticipate voltage offset and drift to increase by a factor of ten in the extended ranges.
3. For band pass models, a 100K Ohms input resistor connects to an internal virtual ground (summing junction). DC inputs are attenuated by filter characteristics and the input may be capacitor-coupled. See next page.

DEFINITIONS

f_c = cutoff or corner frequency of a low pass filter measured at -3dB attenuation.

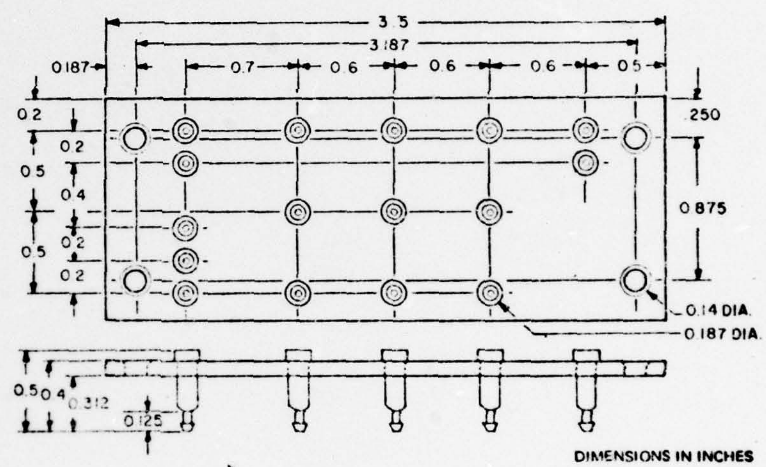
f_o = pass band center frequency of a band filter, equals $\sqrt{f_H f_L}$

f_L = lower -3dB pass band frequency of a band pass filter.

f_H = upper -3dB pass-band frequency of a band pass filter.

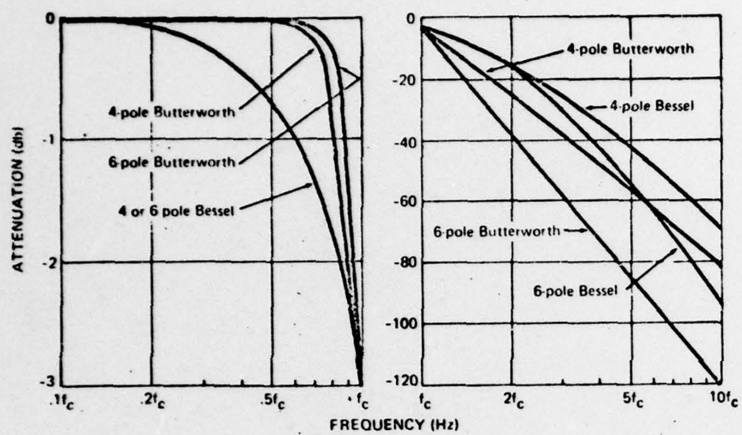
Q = selectivity, defined as $\frac{f_o}{f_H - f_L}$

MATING SOCKET MS-12



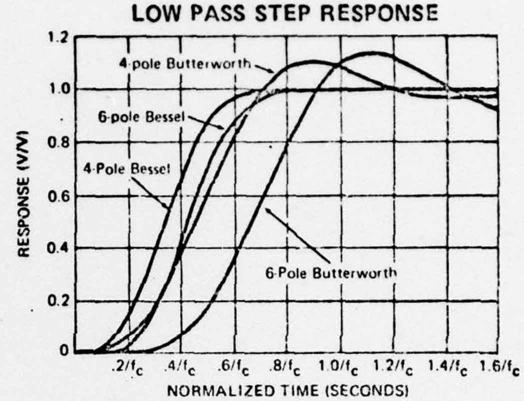
TYPICAL RESPONSE CHARACTERISTICS – NORMALIZED FREQUENCY

LOW PASS ATTENUATION

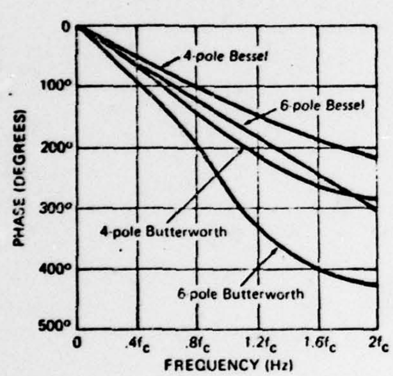


Notes: All curves normalized to f_c = 1 Hz where f_c is defined as the -3db point for both Butterworth and Bessel.

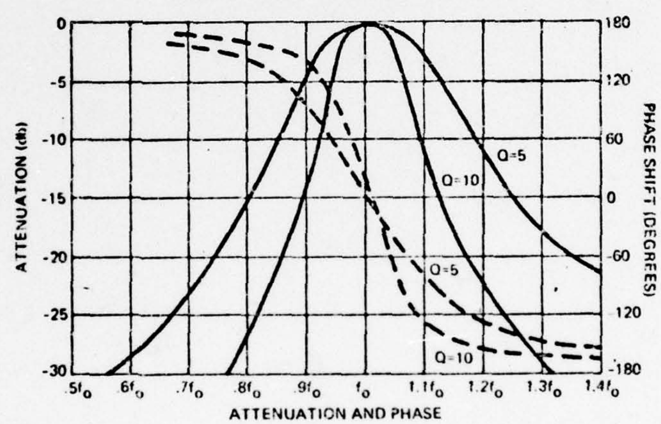
LOW PASS STEP RESPONSE

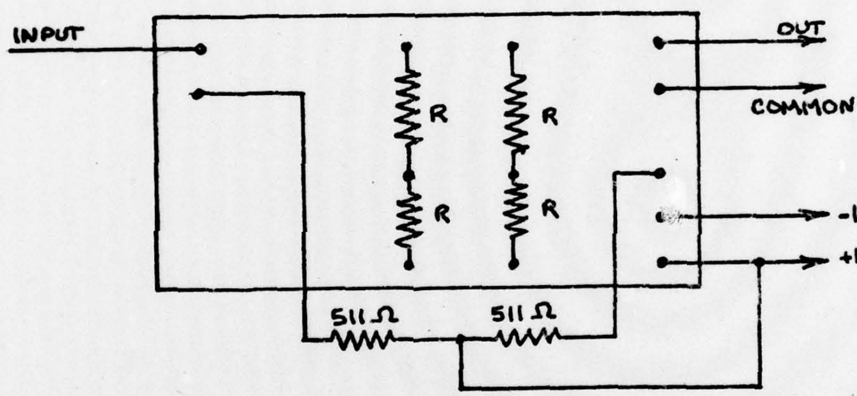


LOW PASS PHASE SHIFT



BAND PASS ATTENUATION





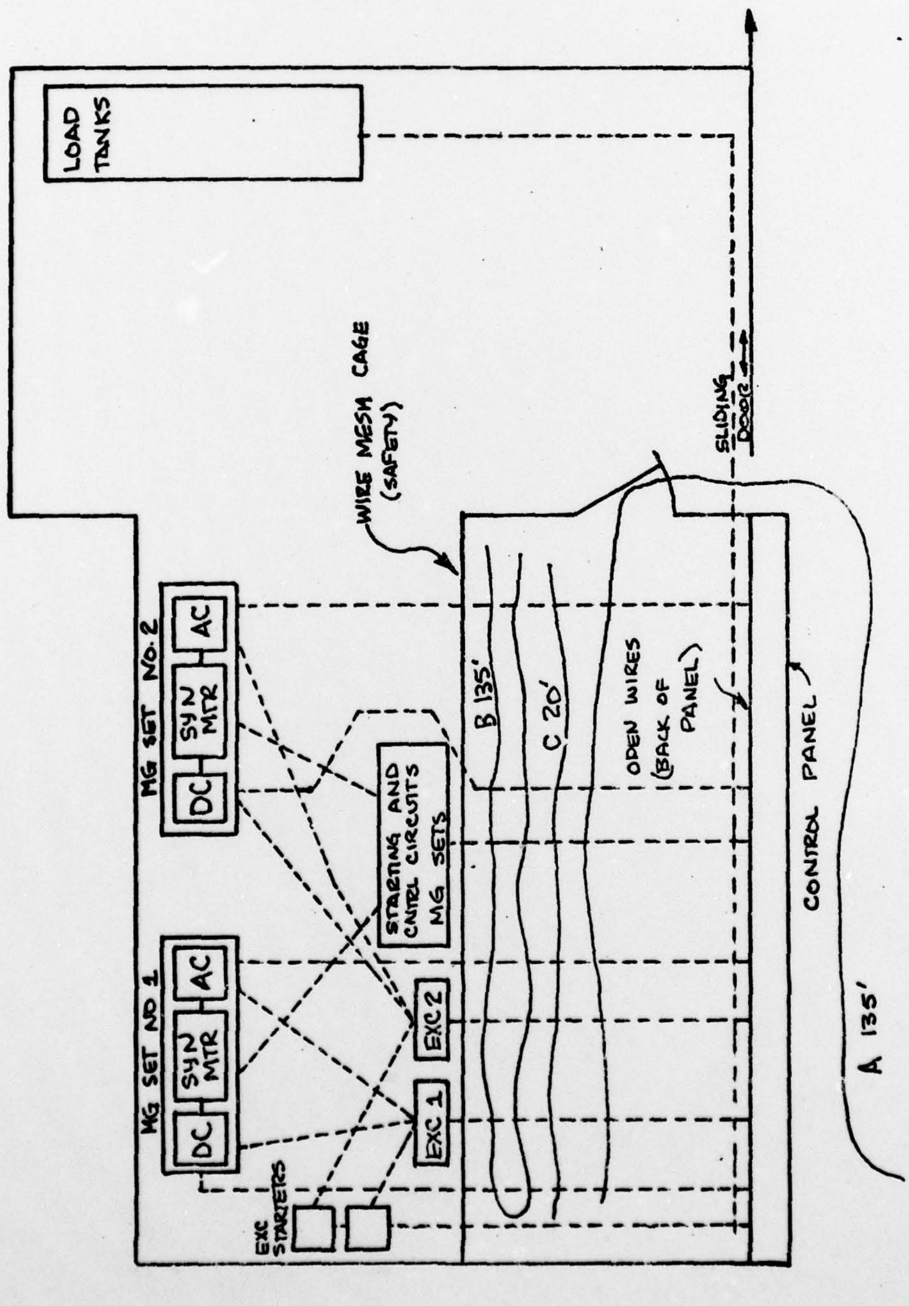
Formula for cutoff frequency

$$\frac{1}{f_c} = \frac{\frac{R(K\Omega)}{2} + 1}{f_c\,(Max)}$$

where f_c (Max) = 500

APPENDIX III

INSTALLED EQUIPMENT LAYOUT AND CABLE LAYOUT FOR MAGNETIC PICKUP MEASUREMENT



APPENDIX IV

INVESTIGATION OF INHERENT FREQUENCIES OF THE AC GENERATION SYSTEM

Trial 1. Exciter: V = 130 volts, (= 39 amps
Measured at input to filter.

Frequency (Hz)	% of full scale
945	100
119	40
Note: 119 Hz was now	set as the 100% reading
29.5	7
59	8
88	5
119	100
185	5
235	8
350	8
470	5
595	4

Trial 2. Exciter: V = 65 volts, I = 21 amps
Measured at input to filter
Comment: as V decreases, tooth ripple decreases

Frequency (Hz)	% of full scale
31	28
62	10
92	4
122	100
186	5
210	0.5
242	4
310	0.5
360	10
490	1
610	3
720	5
965	98

Trial 3. Exciter: V = 130 volts, (= 20 amps
Measured at input to filter
Comment: tooth ripple back to its original value

Frequency (Hz)	% of full scale
121	19
955	100
Note: 121 Hz was now set as the 100% reading	
30.5	14
62	13 (±3, fluctuates)
90	3
121	100
185	5
241	18
360	12
482	9

Trial 4. All machines off and the switch closed
Measured at input to filter

Frequency (Hz)	% of full scale
62	100
185	24
310	6

APPENDIX V

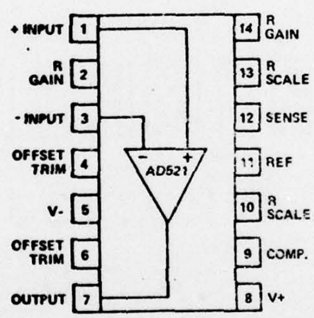
INSTRUMENTATION AMPLIFIER SPECIFICATIONS (AD 521J)

SPECIFICATIONS

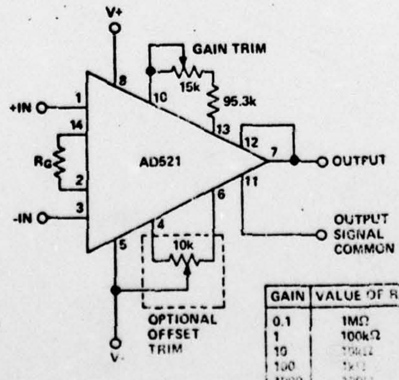
(typical @ V_S = ±15V, R_L = 2kΩ and T_A = 25°C unless otherwise specified)

MODEL	AD521J
GAIN	
Range (For Specified Operation, Note 1.)	1 to 1000
Equation	$G = R_S/R_G$ V/V
Error from Equation	(±0.25–0.004G)%
Nonlinearity (Note 2)	
1≤G≤1000	0.1% max
Gain Temperature Coefficient	±(3 ±0.05G)ppm/°C
OUTPUT CHARACTERISTICS	
Rated Output	±10V, ±10mA min
Output at Maximum Operating Temperature	±10V @ 5mA min
Impedance	0.1Ω
DYNAMIC RESPONSE	
Small Signal Bandwidth (±3dB)	
G = 1	>2MHz
G = 10	300kHz
G = 100	200kHz
G = 1000	40kHz
Small Signal, ±1.0% Flatness	
G = 1	75kHz
G = 10	26kHz
G = 100	24kHz
G = 1000	6kHz
Full Peak Response (Note 3)	100kHz
Slew Rate, 1≤G≤1000	10V/μsec
Settling Time (any 10V step to within 10mV of Final Value)	
G = 1	7μsec
G = 10	5μsec
G = 100	10μsec
G = 1000	35μsec
Differential Overload Recovery (±30V Input to within 10mV of Final Value) (Note 4)	
G = 1000	50μsec
Common Mode Step Recovery (30V Input to within 10mV of Final Value) (Note 5)	
G = 1000	10μsec
VOLTAGE OFFSET (may be nulled)	
Input Offset Voltage (V_{os_I})	3mV max (2mV typ)
vs. Temperature	15μV/°C max (7μV/°C typ)
vs. Supply	3μV/%
Output Offset Voltage (V_{os_O})	400mV max (200mV typ)
vs. Temperature	400μV/°C max (150μV/°C typ)
vs. Supply (Note 6)	0.005V_{os_O}/%
INPUT CURRENTS	
Input Bias Current (either input)	80nA max
vs. Temperature	1nA/°C max
vs. Supply	2%/V
Input Offset Current	20nA max
vs. Temperature	250pA/°C max
INPUT	
Differential Input Impedance (Note 7)	3×10^{9}Ω‖1.8pF
Common Mode Input Impedance (Note 8)	6×10^{10}Ω‖3.0pF
Input Voltage Range for Specified Performance	±10V
Maximum Voltage without Damage to Unit, Power ON or OFF Differential Mode (Note 9)	30V
Voltage at either input (Note 10)	V_S ±15V
Common Mode Rejection Ratio, DC to 60Hz with 1kΩ source unbalance	
G = 1	70dB min (74dB typ)
G = 10	90dB min (94dB typ)
G = 1000	100dB min (104dB typ)
G = 1000	100dB min (110dB typ)

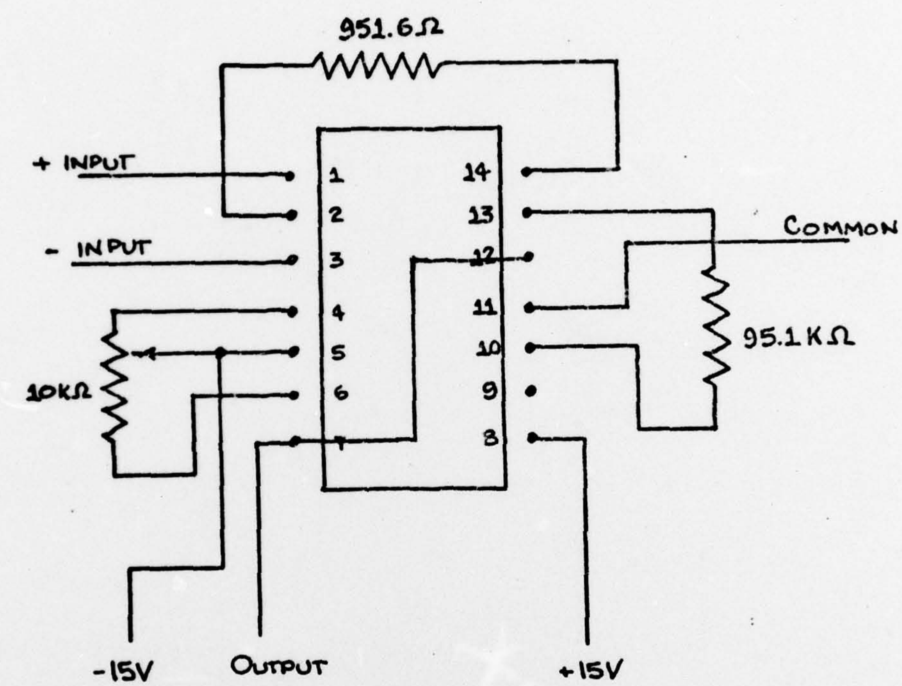
NOISE	
Voltage RTO (p-p) @ 0.1Hz to 10Hz (Note 10)	$\sqrt{(0.5G)^2 + (150)^2}\ \mu V$
RMS RTO, 10Hz to 10kHz	$\sqrt{(1.2G)^2 + (30)^2}\ \mu V$
Input Current, rms, 10Hz to 10kHz	15pA(rms)
REFERENCE TERMINAL	
Bias Current	3μA
Input Resistance	10MΩ
Voltage Range	±10V
Gain to Output	1
POWER SUPPLY	
Operating Voltage Range	±5 to ±18
Quiescent Supply Current	5mA max
TEMPERATURE RANGE	
Specified Performance	0 to +70°C
Operating	-25 to +85°C
Storage	-65 to +150°C
PRICE	
(1-24)	$12.75
(25-99)	$10.20
(100-999)	$8.50



TOP VIEW



GAIN	VALUE OF R_G
0.1	1MΩ
1	100kΩ
10	[illegible]
100	[illegible]
1000	[illegible]


951.6Ω
+ INPUT
- INPUT
10KΩ
1
2
3
4
5
6
7
14
13
12
11
10
9
8
COMMON
95.1 KΩ
-15V
OUTPUT
+15V

APPENDIX VI

TRANSFORMER CONNECTIONS FOR CAPACITANCE MEASUREMENT